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Volume II

Study Results

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Space Tug Docking Study

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SPACE TUG DOCKING STUDY

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FOREWORD

This study was performed under Contract NAS8-31542 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the direction of Mr. James I. Newcomb and Mr. Paul T. Craighead, the Contracting Officer's Representatives. The final report consists of five volumes:

Volume I - Executive Summary
Volume II - Study of Results
Volume III - Procedures and Plans
Volume IV - Supporting Analyses
Volume V - Cost Analysis

The study results were developed during the period from June 1975 to January 1976. Principal Martin Marietta contributors to the study were:

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ACRONYMS & ABBREVIATIONS

ACS	Attitude Control System
A/D	Analog to Digital
ATP	Authorization to Proceed
CDC	Control Data Corporation
CDR	Critical Design Review
cg or c.g.	center of gravity
CRT	Cathode Ray Tube
D/A	Digital to Analog
db	decibels
DOF	Degrees of Freedom
EREP	Earth Resources Experiment Program
FM/CW	Frequency Modulated/Continuous Wave
FOI	First Order Interpolator
FOP	First Order Predictor
FOV	Field of View
ft	feet
fps or f/s or ft/sec	feet per second
GaAs	Gallium Arsenide
GDC	General Dynamics Convair
GSE	Ground Support Equipment
IBM	International Business Machines
ICW	Interrupted Continuous Wave
IF	Intermediate Frequency
I/F	Interface
IMU	Inertial Measurement Unit
IOC	Initial Operational Capability
ITT	International Telephone and Telegraph
KBS or Kps	Kilobits per second
kg	kilogram
KHz	Kilohertz (kilocycles)
kw	kilowatt
lb	pounds
LLLTV	Low Light Level Television
LM	Lunar Module
LOS	Line-of-sight
m	meter
MBPS	Megabits per second
MDAC	MacDonnell Douglas Aerospace Corporation
MHz	Mega hertz (mega cycles)
MMC	Martin Marietta Corporation
MMSE	Multi-Use Mission Support Equipment
mps or m/s	meters per second
MTBF	Mean Time Between Failure
N/A	Not Applicable
nm or n. mi.	nautical mile
N/R	Nonrecurring
OTV	Orbital Transfer Vehicle
PCM	Pulse Code Modulation

ACRONYMS & ABBREVIATIONS (Cont'd)

Pd	Probability of Detection
PDR	Preliminary Design Review
P_{fa}	Probability of False Alarm
PRF	Pulse Repetition Frequency
R	Range
$\dot{R}$	Range Rate
rf or RF	radio frequency
RFP	Request for Proposal
RSS	Root Sum of the Squares
R/V	Rendezvous
R/V&D	Rendezvous and Docking
S/C or s/c	Spacecraft
SIT	Silicon Intensified Target
SLR	Scanning Laser Radar
S/N	Signal-to-Noise
STEM	Storable Tubular Extendible Member
STDN	Space Tracking Data Network
TBD	to be determined
TDRSS	Tracking, Data, Relay Satellite System
TV	Television
USB	Unified S-band
V	Velocity
VP	Video Processor
w	watt
w/r	with respect to
wt	weight
ZOI	Zero Order Interpolator
ZOP	Zero Order Predictor
μ sec	Microsecond (10^{-6} sec)

REFERENCES

1. "Video Guidance, Landing and Imaging Systems for Space Missions", NASA CR-132746, Final Report, Contract NAS1-13558, Martin Marietta Corporation, December 1975.

2. "Space Tug Avionics Definition Study", CASD-NAS75-012, Final Report, Contract NAS8-31010, General Dynamics Convair Div., April 1975.

3. "Laser Space Rendezvous and Docking Tradeoff", 1247 R 0004, Interim Report, Contract NAS8-30738, Norden Div. of United Aircraft, December 1974.

4. "Design of a Scanning Laser Radar for Spaceborne Applications", Phase III Report, Contract NAS8-23973, ITT Gilfillan, Van Nuys, California, October 1971.

5. "Construction and Testing of a Scanning Laser Radar", Phase II Report, Contract NAS8-20833, ITT Gilfillan, Van Nuys, Calif., December 1971.

6. "Development of Generation #3 Scanning Laser Radar", Phase III Report, Contract No. NAS8-20833, ITT Gilfillan, Van Nuys, Calif., January 1974.

7. "Baseline Space Tug Configuration Description", 68M00039-2, Marshall Space Flight Center, July 15, 1974.

8. "IUS/Tug Payload Requirements Compatibility Study", Contract NAS8-31013, McDonnell Douglas; May 1975.

9. "Space Tug/Shuttle Interface Compatibility Study", Contract NAS8-31012, General Dynamics Convair; San Diego, Calif., June 1975.

10. "IUS/Tug Orbital Operations and Mission Support Study", Contract NAS8-31009, Final Report, IBM, Huntsville, Alabama, May 1975.

11. "Tracking Techniques for Space Shuttle Rendezvous", Contract NAS9-13-576, RCA, Burlington.

12. "FM/CW Terminal Guidance Radar for Noncooperative Rendezvous", Interim Report MMC No. 73-48865-002 on IRAD No. D10-S, Martin Marietta Corporation, June 1973.

13. "Video Guidance, Landing and Imaging System for Space Missions", Final Report, No. NASA CR-132574, Martin Marietta Corporation, February 1975.

14. "Cooperative Six Axis Sensor for Teleoperator", New Technology Disclosure, NASA No. NPO 13386; JPL 3043; Alan Johnson, Jet Propulsion Lab, Pasadena, Calif., June 14, 1973.

15. "Teleoperator Controls", AEC-NASA Technology Survey, NASA SP-5070, December 1968.

16. "Space Rendezvous, Rescue and Recovery", Vol. 16 part one of the AAS, "Advances in the Astronautical Sciences", Technical Sessions, September 10, 1963.

STUDY RESULTS

I. INTRODUCTION

This study has been directed at the rendezvous and docking operations associated with the full capability Space Tug. It has investigated all of the associated technologies, selected and ranked alternate mechanizations capable of performing required operations, and recommended development activities that will lead to a proven system design. While this study has been directed at only one of the rendezvous and docking applications to be encountered in the next decade, the findings are pertinent to several STS applications that can be foreseen. As a consequence, these study results have a general value beyond the specific study objectives.

A. OBJECTIVES & EMPHASIS

These specific objectives for the Space Tug Docking Study were outlined in the original request for proposal as follows. First, to define, through a total systems analysis, requirements, techniques, schemes, mechanisms, components and subsystems for rendezvous and docking operations. Second, synthesize candidate rendezvous and docking systems providing rationale through analysis for their selection. Third, recommend through an evaluation of relative merits the best manual, automated and hybrid systems. And finally, provide plans for the accomplishment of the simulation/demonstration testing of the selected systems.

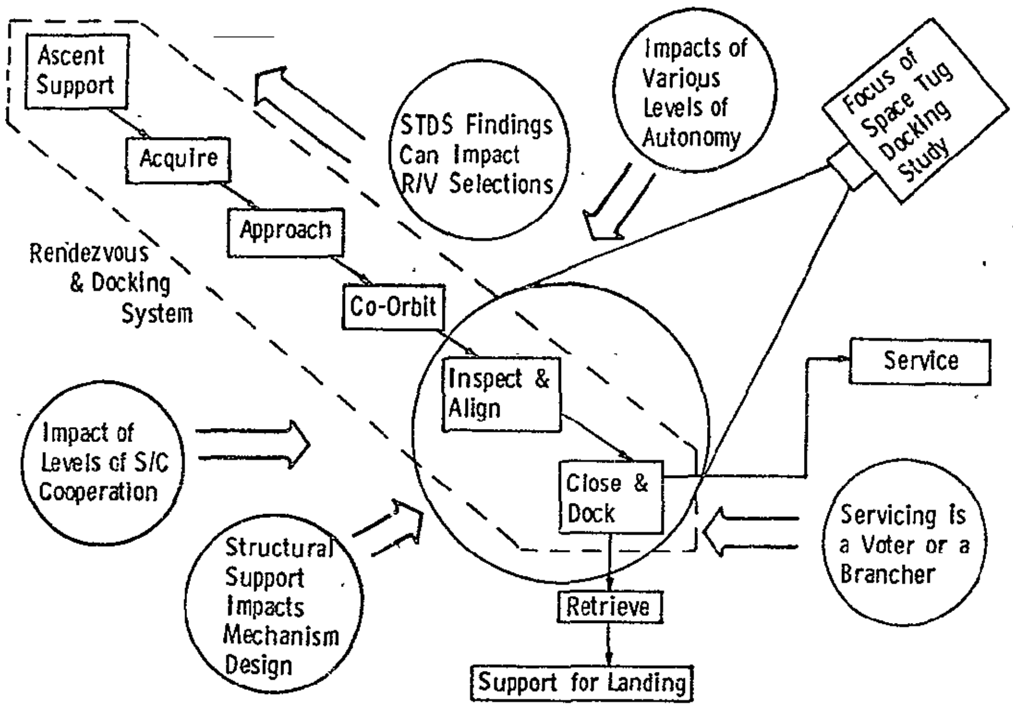


Fig. I-1 Study Focus

Figure I-1 illustrates the operations that are involved with rendezvous and docking, together with the ultimate result of Tug R/V & D activity -- which will either be servicing or retrieval of a spacecraft. This study concentrates on the inspect, align, close and dock operations. The reason for this concentration is that a considerable amount of recent or concurrent effort has been directed at the other operations. It has been the intent of this study to build upon and supplement these other activities.

Several of these study relationships are particularly significant. First, the General Dynamics Tug Avionics Study has defined a highly accurate navigation system based upon updates received from an Interferometer Landmark Tracker. The accuracy of this system minimizes the range of initial conditions over which the R/V & D system must operate. This GDC study also recommended a particular R/V &D system mechanization. This system has been taken into account in the current study, but investigation of various levels of autonomy and spacecraft cooperation as well as more detailed docking evaluation has led to several alternate system recommendations.

The MDAC Payload Requirements Compatibility Study and the MMC Multi-Use Mission Support Equipment Study have investigated the problems of supporting (structural support, particularly) retrieved spacecraft. The problem of meeting docking requirements and structural support requirements on return into the Shuttle payload bay for return to earth is particularly complex and involves significant trades. This study builds on the findings of these two studies, compares, and recommends some new alternatives.

The MMC Integrated Orbital Servicing Study investigated the basis for the selection of a cost effective orbital maintenance system supported by the space transportation system. The conclusions and recommendations reached during this servicing study effort have been taken into account in the STDS effort. Compatibility with servicing is considered a desirable goal, and has been taken into account in the selections and rankings developed here.

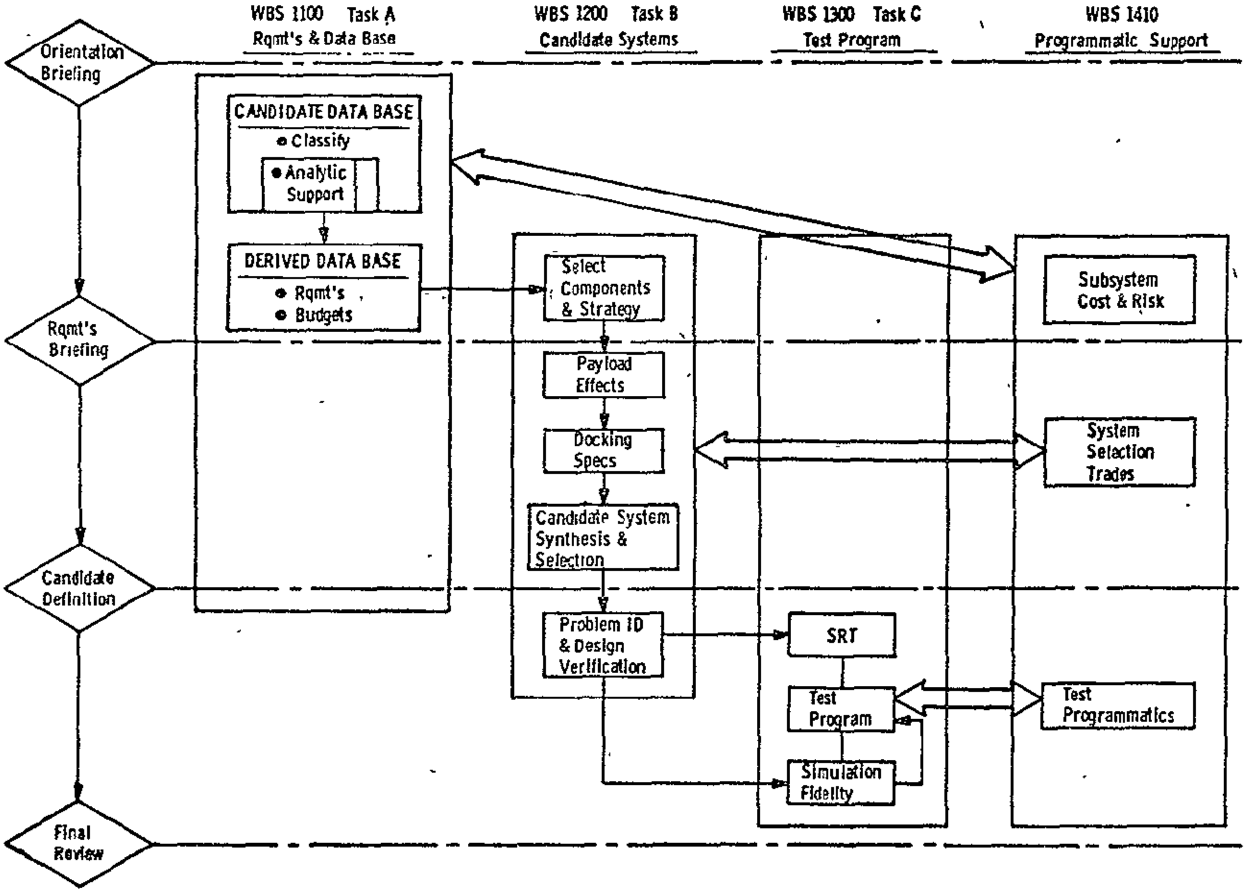


Fig. I-2 Organization of Study

B. STUDY ORGANIZATION

The STDS study effort was organized to support study objectives. Fig. I-2 shows the task structure employed. Task A generated requirements, developed a component/strategy data base and supplied analytic support for the study effort. Requirements and data base information was compiled early in the study and changed minimally afterward. Analytic support in the areas of flight mechanics and docking dynamics continued throughout the study. Task B concentrated on synthesizing candidate systems (manual, autonomous and hybrid types) capable of meeting the requirements defined in and comprising the data base generated in Task A. These systems were then ranked based on criteria developed and weighted with a sensitivity to functional requirements, operational and cost objectives. An evaluation of developmental problems associated with the candidate systems selected lead into the Task C effort, where SRT and Simulation/Demonstration objectives and

plans were evolved. The SIM/DEM plans evolved married developmental requirements to MSFC laboratory facilities, supplementing with other test facilities when required, recommending MSFC facility modification where applicable. This total effort was supplemented by programmatic analyses to provide realistic and cost conscious background data to support decisions and recommendations.

This Volume II of the final reporting presents a complete view of the results of the studies described in the preceding paragraph. Volume I is an executive summary; Volume III is a compilation of procedures and plans; Volume IV is an appendix of supporting analyses and Volume V presents programmatic data developed. This volume is organized according to the major study tasks (A, B & C) with an added summary of study recommendations.

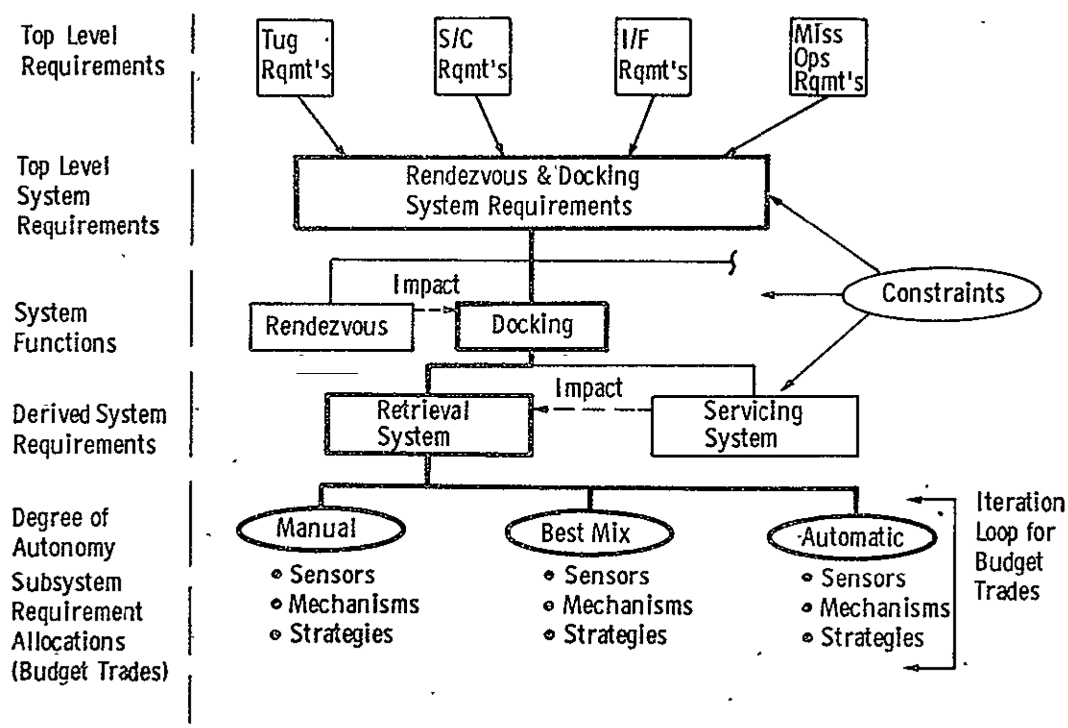


Fig. I-3 Requirements Hierarchy

C. STUDY APPROACH

The development of requirements for the rendezvous and docking system was a top-down process, starting at top level systems requirements and ending at individual subsystem requirement allocations. The areas where specific requirements

summaries were developed in this study are heavily outlined in Fig. I-3. This concentration reflects the study emphasis described in Fig. I-1. Note that the subsystem level requirements allocation was an iterative process, beginning with broad estimates and improving as analysis tools were developed and applied during the study. The detailed results of these analyses and developments are presented in Section II of this report.

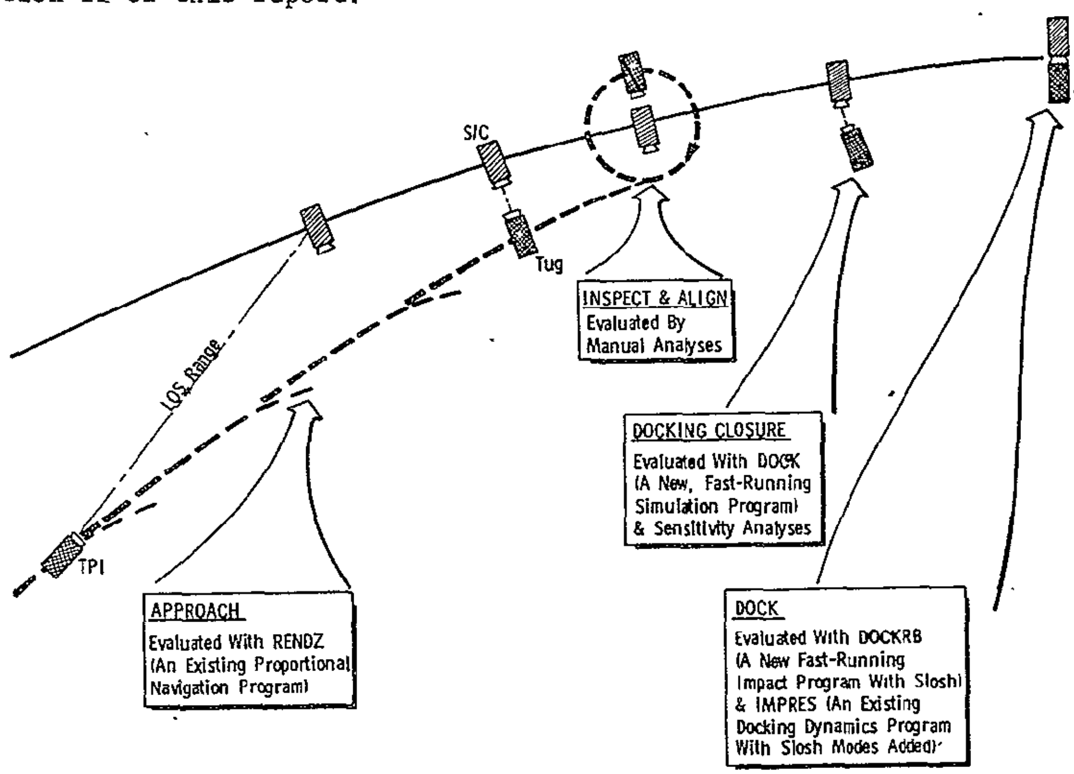


Fig. I-4 Analysis Approach

A blend of manual analyses, existing/modified simulation programs, and new simulation programs were used to support this study effort. The relationship between these programs and the operational phases they supported are illustrated in Fig. I-4. The depth of analysis presented in this study has been somewhat varied, but consistent with study objectives. It has been a superior effort, in relation to the dollar value of the study. These activities do, of course, suggest further activity: formal simulation of the inspection maneuvers; expansion of the docking simulation from planar to 3-D space; detailed application of the docking dynamics programs to more detailed specification of docking mechanism parameters (e.g. damping, spring constants, et al).

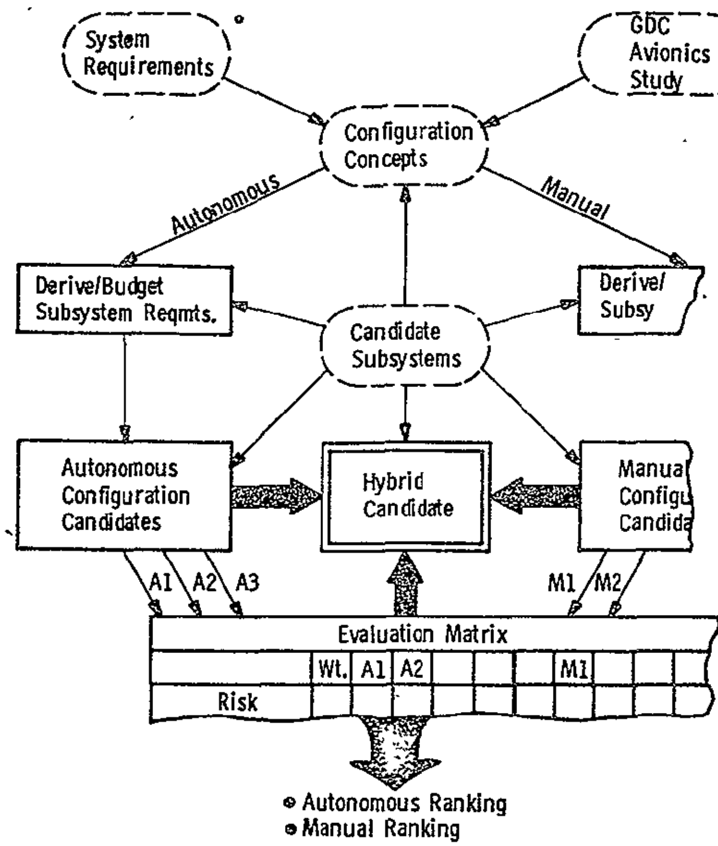


Fig. I-5 System Configuration & Selection Approach

The system configuration and ranking process used in this study is depicted in Fig. I-5. This process involved generation and ranking of a set of manual candidates and a set of autonomous candidates. Using the evaluations of the manual and autonomous candidates, a single hybrid system combining the best features of both was evolved. Each of these system candidates is capable of meeting system level requirements defined under Task A. The ranking process used to identify the more promising system candidates used a numerical approach. The candidates were compared over a range of selection criteria (cost, performance and growth potential parameters). Numerical rankings were weighted to reflect relative importance and summed to establish a comparable figure of merit. The top ranking candidates were used to establish SRT and SIM/DEM requirements.

The basic philosophy behind the developmental activity defined during this study has been practical. The top ranking system candidates have been evaluated to identify long lead component development requirements, and areas where operational problems may develop. Plans have been evolved to assure that these

requirements/operations are addressed in a timely manner -- to assure that potential problems are understood and worked out before expensive developments have proceeded too long down the wrong path. This kind of attention early in a development program is sure to save money in the long term. The only hazard is the possibility of changing requirements as the program evolves. This possibility requires continued integration of new requirements running in parallel to SRT and SIM/DEM activity.

D. MAJOR STUDY FINDINGS

Current technology, conventional RF-RADAR and video systems, easily accommodates remote rendezvous and docking in the manual mode where real time ground support is used to direct the sequence of events. Autonomous docking requires some relatively low risk new development work -- either flight qualification of the proven GaAs Scanning Laser Radar or advancement of autonomous TV docking algorithms.

Hybrid systems are most attractive as they provide a desirable level of redundancy, provide flexibility to accommodate unforeseen events. Hybrid systems offer a low risk approach to the development of an autonomous rendezvous and docking capability. Thus the hybrid approach is the most feasible development option. Early flights can be made with heavy manual supervision. As confidence is gained, autonomous approaches can be verified -- eventually evolving a flexible rendezvous and docking capability able to operate effectively in any situation.

Attractive alternate development paths are available in close-in RF docking sensors and in non-impact docking mechanisms. Close-in RF sensing, to within one or two feet of the target, is possible using passive (no power required) time delay retroflectors on the spacecraft. This approach has the advantage of using flight proven technology, although new component development/qualification would be required. Non-impact docking is achievable through the use of a close-in station keeping mode coupled with an articulated docking device (e.g. a steerable STEM device). This approach has the advantage of a simple structural interface between Tug and retrieval spacecraft, and a potential for minimal impact on the spacecraft. It is felt that these options should be kept open until future rendezvous and docking requirements are more completely understood.

E. RECOMMENDED FUTURE ACTIVITY

Three major types of future activity are recommended as a result of this study. The first category is the Simulation/Demonstration activity that has been defined in the Task C effort. Pursuit of this laboratory testing activity affords a technique for economically selecting between development options, arriving at a proven design approach soundly based on an adequate simulation of anticipated flight conditions.

The second category is the specific technology areas that have been identified during the study. These areas include development and application of digital simulation tools, flight algorithm development, and design effort required to advance alternate design options. These activities should be pursued over the next 2-3 years and then either discarded or integrated into the SIM/DEM activity.

The final category is a broad integration role that should be begun immediately and continued throughout the STS operational life. It is apparent that the role of rendezvous and docking in future space operations is expanding. Many applications are emerging that can benefit from the technology surveyed in this study. An initial activity in this integration role is an applications system study to place varied future requirements in perspective and define overall development/operation plans that will most effectively meet all objectives. The implementation of these plans leads to an integration role that on one hand pursues the development of a rendezvous and docking capability, and on the other hand supports operational activities throughout the active life of this capability.

II. REQUIREMENTS AND DATA BASE

Previous studies have been conducted for many aspects of Space Shuttle, Space Tug and payloads which assume a rendezvous and docking capability. The Space Shuttle Payload Description Activity (SSPDA), the NASA Mission Model and the Baseline Space Tug requirements documents are examples. Also, a significant amount of research and development work has been underway in developing new subsystems which are useful for rendezvous and docking.

However, there has been no concerted effort to research these areas and derive a set of requirements for a rendezvous and docking system, nor to catalog the existing candidate sensor, mechanism or strategy characteristics. The object of this task was to accomplish these goals.

Additionally, analyses were performed to evaluate rendezvous and docking schemes and to determine effects of docking dynamics.

A. SYSTEM REQUIREMENTS DERIVATION

Rendezvous and Docking System requirements were derived from many sources as well as generated from engineering analyses. Additionally, desirable features of a docking system were identified and used as weighting factors for selection of candidate subsystems. The major sources of requirements were Space Tug, Spacecraft, Interface and Operations documents. The key system level docking requirements from these areas are illustrated in Figure II-1 and are described in more detail in the following paragraphs.

Requirements derive from many sources; a complete tabulation of all system level requirements with traceability to appropriate documentation may be found at the end of this section. (Table II-7).

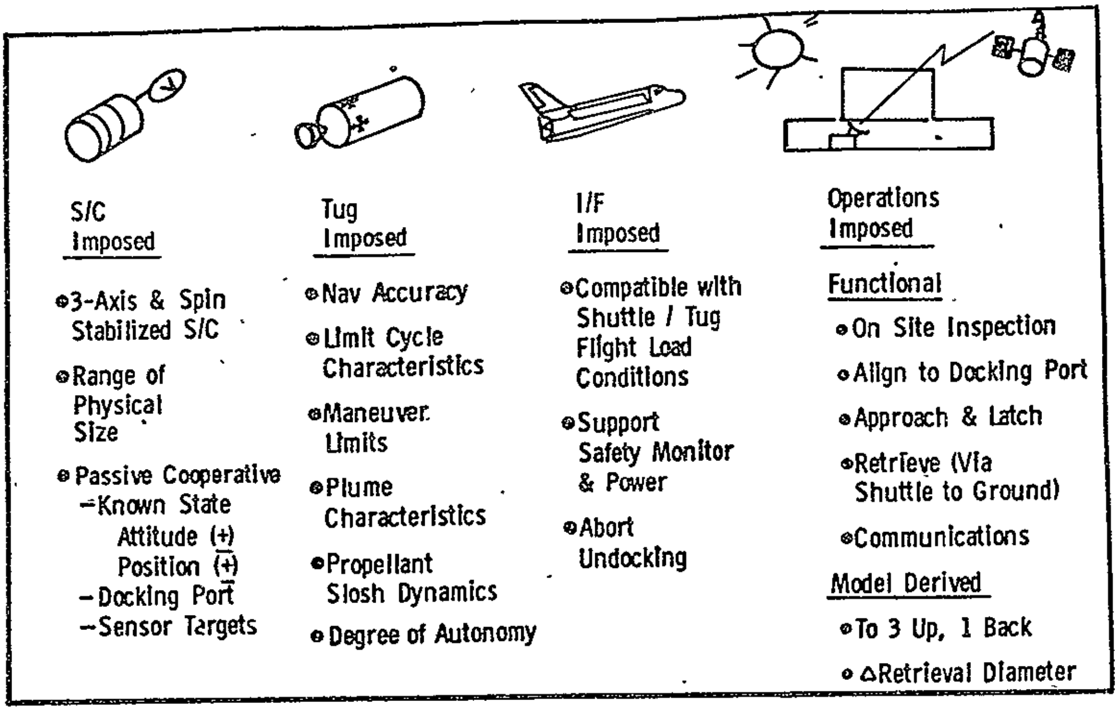


Figure II 1: Requirements derive from many sources

1. <u>Spacecraft Imposed Requirements</u> - Since the spacecraft developers will become the users of this system, the desired features were considered heavily in the candidate selection. The user acceptance of this service will be a determining factor in the economic feasibility of a docking capability, whether it is used in a retrieval or servicing role.

Those requirements which derive from spacecraft sources as well as those desirable features of a docking system from a spacecraft standpoint are summarized in Table II-1.

a) <u>Reference Spacecraft Selection</u> - In order to bound the range of driving requirements which must be accommodated by the system, a set of reference spacecraft were selected for the study. Four spacecraft were found to provide an adequate range of parametric variations as illustrated in figure II-2.

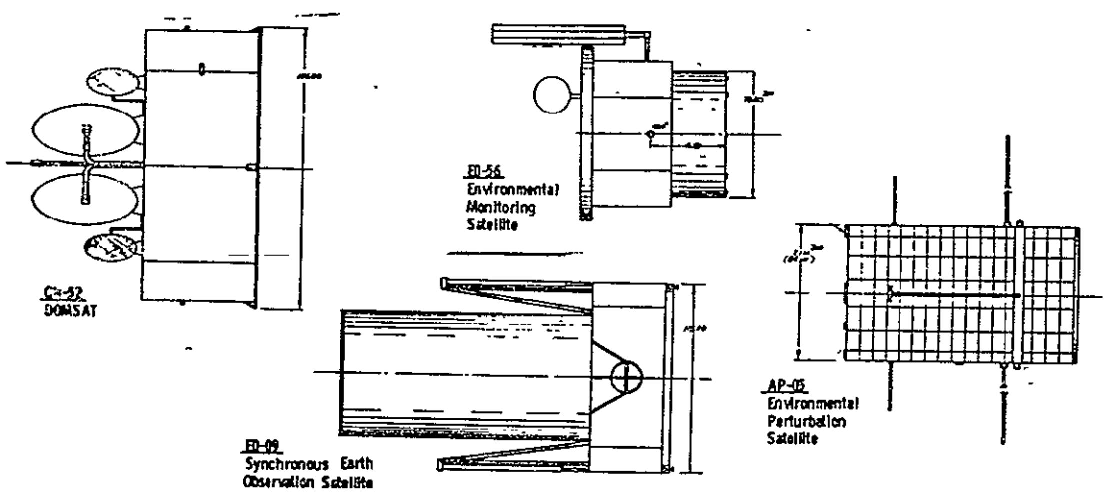
Table II-1 Requirements from Spacecraft Sources

The Docking System Must Accommodate:

- Wide Range of Spacecraft Size / Weights
- Variations in Stabilization Systems (3-Axis vs Spin)
- Passive Cooperative Spacecraft
- Known S/C State Intelligence

The Docking System Should:

- Minimize Spacecraft Design Impacts
- Provide for Infant Mortality Retrieval
- Not Interfere with Servicing
- Consider Non-Cooperative Spacecraft Retrieval



Parameter	CN-52 Domsat	E0-09 Synchronous Earth Observation Satellite	E0-56 Environmental Monitoring Satellite	AP05 Environmental Perturbation Satellite A
Orbital Altitude	Geostationary	Geostationary	1686 km (910 nmi)	1282 km (6900 nmi)
Orbital Inclination	0 rad (deg)	0 rad (deg)	1.8 rad (103 deg)	.96 rad (55deg)
S/C Length	3.6 m (12 ft)	7.5 m (25 ft)	3.6 m (12 ft)	3.6 m (12 ft)
S/C Mass	561 kg (1237 lb)	1481 kg (3266 lb)	2183 kg (4814 lb)	1373 kg (3028 lb)
Type Stability	Spin	3-Axis	3-Axis	3-Axis
Booms	No	No	No	Yes
Solar Panels	No	Yes	Yes	No
Pointing	Earth	Earth	Earth	Inertial

Figure II-2 Reference Spacecraft Bound the Requirements

Most existing mechanism designs could be eliminated by the system level requirement to deliver one diameter spacecraft and retrieve another. Other factors considered in the analyses included servicing, infant mortality retrieval and impacts of docking with non-cooperative spacecraft.

Since the STDS charter was for a system to retrieve spacecraft, the capability to service was not imposed as a requirement. The approach for the study was to evaluate the candidate systems based on servicing potential capability and rank each system on this basis.

The capability for infant mortality retrieval of spacecraft has numerous implications. A prime requirement is that spacecraft status be ascertained while the space tug or delivery vehicle is in the vicinity. If this service is provided for all spacecraft delivered, including those for which retrieval was not planned, docking aids/mechanisms must be provided. Also, the spacecraft mortality can occur after partial deployment of appendages and jettison of these appendages plus safing of the spacecraft before recovery must be assured. Implications to the tug include a stationkeeping capability with TV observing the spacecraft for status. This requires mission control involvement with man-in-loop and operational planning for alternate missions/sequences and detection and correction capabilities be provided via RF links.

An analysis of spacecraft top-level functional failure modes and the retrieval capability of a malfunctioning (non-cooperative) spacecraft. At this stage of spacecraft design definition the analysis was necessarily gross in nature with an objective of determining an estimated percentage of spacecraft failure types which are potentially retrievable. Thirteen major types of failures were identified for each spacecraft. Some of the results, as a percent of total failure modes, are provided in tabular form below, followed by some conclusions.

	Three-Axis	Spin
Retrieval not feasible at all	7%	0%
Retrieval potential high (stable vehicle)	15%	46%
Retrieval feasibility depends on inspection	61%	38%
Vehicle state is known on ground	38%	30%
Vehicle state is not known on ground	38%	46%
Vehicle state uncertain	24%	24%

Retrieval of failed spacecraft, particularly spin-stabilized, appears feasible in a number of instances. Only a very small percentage of failure modes leaves the spacecraft in a totally nonretrievable state.

The potential of retrieval of a high percentage of spacecraft failure modes (over 50% for either type) depends on an inspection by the tug. There is considerable hesitation to expend a lot of orbital energy in pursuit of a spacecraft whose retrievability is not known until rendezvous with it. To alleviate that unknown, it might be worth requiring that every spacecraft has some low-bit-rate method of dumping vehicle status to the ground from an omni antenna when a failed condition arises in order to gain some likelihood of retrievability.

The large percentage of spacecraft failure modes requiring inspection before retrieval, and the unknowns involved in making a "retrieve" decision, virtually dictate a man in the loop for failed spacecraft retrieval. Trades between manual, autonomous, and hybrid should consider this seriously when looking at growth from an operative to a failed spacecraft retrieval capability.

Knowledge of vehicle state, e.g., attitude and rates, is not known, or at least uncertain, for well over half the possible failed spacecraft conditions. Assuming the inspection phase has found docking feasible, it is necessary for the tug to determine the spacecraft attitude and rate prior to LOS tracking during closure. This capability impacts hardware sensors, cooperative devices and modes of operation. Candidate selections should be made considering growth to the capability for determining the vehicle state necessary to accomplish this.

2. Tug Imposed Requirements - Those requirements which derive from Tug sources as well as the desirable features of a docking system from the tug standpoint are summarized in Table II-2.

The uncertainties in tug position and attitude, as well as spacecraft position and attitude must be accommodated by the Docking System. This, in effect, reduces the available system budget which can be allocated to the sensors or increases the uncertainties which must be accommodated by the mechanisms. Figure II-3 illustrates the Space Tug Control System characteristics and a typical three-axis stabilized spacecraft limit cycle deadband.

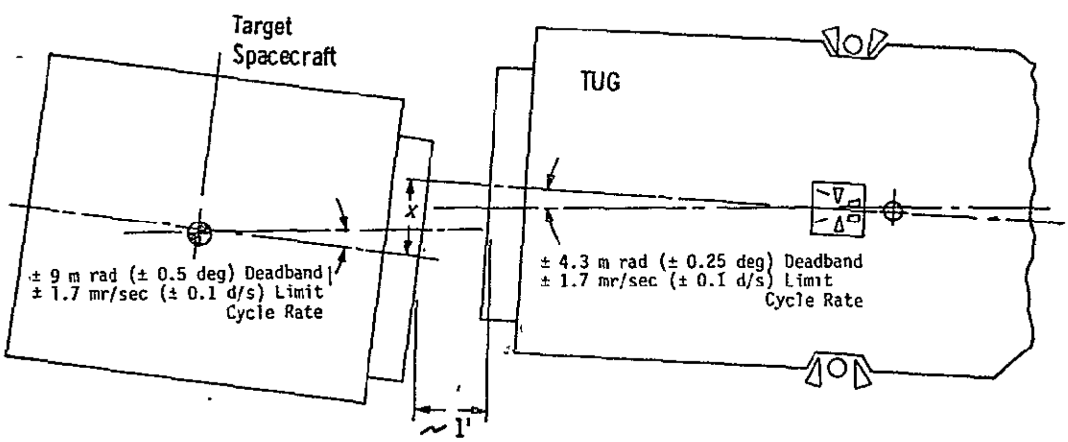
Table II-2 Requirements from Tug Sources

The Docking System Must Accommodate:

- Tug Guidance / Navigation Uncertainties
- Tug Attitude Control Deadbands
- Tug Provided Services to S/C
- Tug Plume Impingement Forces
- Tug Propellant Slosh Dynamics

The Docking System Should:

- Minimize Tug Design Impacts
- Utilize Tug Onboard Data Management Resources



Parameter	Uncertainties	GDC Baseline Budget
Angular Error (Σ Deadbands)	13 m rad 0.75 deg)	.09 rad (5.0 deg)
Angular Rate (Σ Limit Cycle Rates)	3.5 mr/sec (0.2 d/s)	9 mr/sec (0.5 d/s)
Maximum Miss Distance (X)	4.6 cm (1.8 in)	30.5 cm (12 in)
Lateral Velocity Error ($\dot{X}$)	1.27 cm/sec (0.5 in/s)	9.1 cm/sec (3.6 in/s)

Figure II-3 Tug Guidance & Navigation Uncertainties Drive Docking System Design

The docking port to c.g. distance for the spacecraft is assumed to be 2.1 m (7 ft) and for the tug, 5.4 m (18 ft). The tug mass is 14,590 kg (1000 slugs) and the pitch or yaw moment of inertia is 48,585 kg-m^2 (37,000 slug-ft^2).

It is also assumed a close-in sensor is employed that maintains a given range and relative attitude as well as lateral translation corrections. The translation corrections are presumed to be provided in much the same way as attitude--by pulsing the side-pointing thrusters to stay within a predetermined translation deadband. For this example it was assumed two jets would fire at a time and only for the minimum impulse time of 20 ms. This pulse results in a lateral rate of .012 inches/sec. The limit cycle deadband limit is taken at .06 inches by assuming an ACS firing to reverse the lateral translation motion no more often than once each five seconds. These assumptions represent a close approximation for the autonomous and hybrid systems. However, for a strictly manual system using a TV, no close-in sensor is baselined and the control system relies on the inertial platform for attitude hold with command inputs for maneuvers.

The docking dynamics effects impose requirements on the system with regard to loads, accelerations and shock attenuation requirements. A major area of investigation during the study was propellant slosh effects. The groundrules, approach definition and results from the dynamics analyses are presented in paragraph D of this section

In the area of Tug supplied services to spacecraft, the docking system must carry the services across the interface. The types of services envisioned for the rendezvous and docking system to support are illustrated in Figure II-4.

3. <u>Interface Imposed Requirements</u> - Those requirements which derive from interface sources can be categorized in two areas; (1) Tug to spacecraft and (2) Shuttle to payload (Tug and spacecraft) interfaces. These requirement sources and the desirable features of a docking system from these interface standpoints are summarized in Table II-3.

The issue of servicing versus retrieval could become a driver in the candidate system selection if servicing were made a requirement in lieu of a desire.

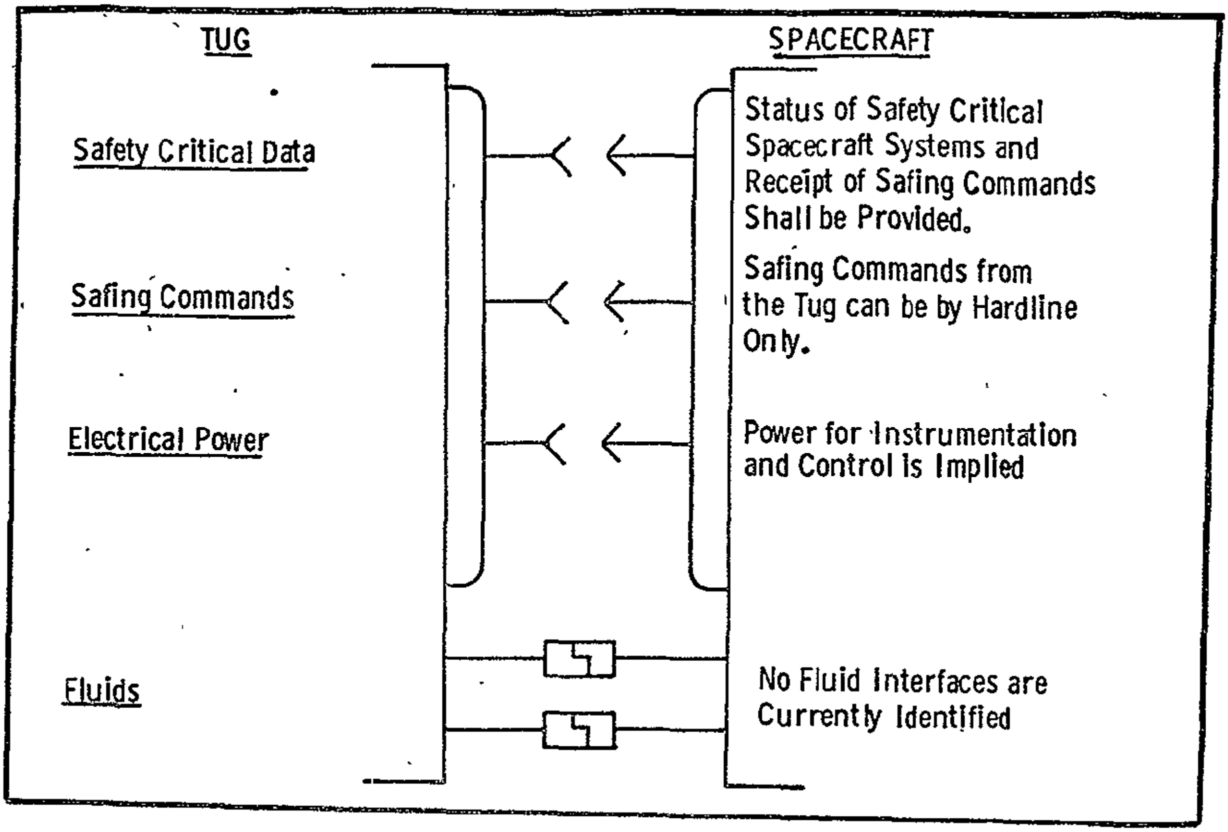


Figure II-4: Rendezvous & Docking System Must Accommodate Spacecraft Services

Table II-3: Requirements from Interface Sources

Interface Imposed Rqmt's -

- Spacecraft / Tug Interfaces
- Payload / Orbiter Interfaces

Interface Considerations / Constraints

- Maximize S/C / Tug Interface Standardization
- Minimize Interface Adapters for Reschedule Flexibility
- Servicing vs Retrieval Interface Considerations
- Impact / Non-Impact Considerations

A summary of the requirements from the interface sources is presented in Table II-4 for Tug/Spacecraft interfaces and Table II-5 for Orbiter/Payload interfaces.

Table II-4: Tug/Spacecraft Interface Requirements

- Spacecraft to Tug Communications Interface is by Hardwire or Via Man-in-Loop
- Safety-Critical Systems (e.g. - Propellants, Ordnance, Cryogenics, Radiation, etc.) Must be Monitored and Determined Safe for Retrieval by Tug, and Subsequently by Orbiter
- Safing Accomplished by Flight Operations (Man-in-Loop) or TV Inspection Plus Umbilical Reconnect for Monitor / Control of S/C
- No Fluid (Propellant, Coolant, Pressurant, etc.) Reconnection Requirements Identified
- Static Discharge Between S/C and Tug Shall be Provided
- Docking System Shall be Compatible with Interface Docking and Abort Undocking Loads

Table II-5: Orbiter/Payload Interface Requirements

- Safety Critical Payload (S/C and Tug) Systems Shall be Monitored & Verified Safe for Retrieval by Orbiter
- Provision Shall be Made to Preclude Depleted Pressurized Tank Implosions During Reentry / Landing
- All Payloads Shall be Compatible with Shuttle Imposed Environments, for Retrieval These Include:
  - Landing Loads (Normal, Abort & Crash)
  - Thermal
  - Accelerations

The requirement from these sources which has a major impact on candidate mechanism selection is the imposition of orbiter abort landing loads. Since the mechanism must support the spacecraft cantilevered off the Tug, this places severe loading design requirements on the mechanism.

4. Operations Imposed Requirements - Operations requirements cover the range of orbital variations and the interfaces with the operations networks. In the process of deriving requirements, consideration must be taken to avoid violation of constraints. Operational flexibility can provide cost effectivity by performing early operations analyses on branching issues such as the servicing versus retrieval roles. For example, a system which can perform both roles may be more or less costly than separate systems. The requirements from operations sources are summarized in Table II-6.

Table II-6: Requirements from Operations Sources

The Docking System Shall Accommodate:
• Payload to Ground Network Compatability (Data Rates) • Network Handover Considerations / Constraints • Orbital Variations (Time Delay, Lighting, etc.) • Manual / Automatic System Crossover / Backups
Operations Considerations / Constraints Shall Be:
• Determined for Impact vs Non-Impact Docking • Determined for Retrieval vs Servicing Missions

An operations analysis which examines the ranges of orbital variations, day/night cycles, time delays and other operational considerations may be found in Section V, Volume IV of this report.

5. System Requirements Summary - Source documents from each of the four areas were reviewed during the early portions of the study to determine those requirements which translate into docking system requirements. These documents included Space Shuttle Payload Definitions (SSPD), MDAC Payload Utilization of Tug (PUT) Study and Spacecraft Requirements Compatibility Study, GDC Avionics Study, IBM Tug/IUS Mission Operations Study and the MSFC Baseline Tug Document set. Other requirements were derived from the STDS request for proposal or from engineering analysis.

The docking system requirements derived in this study and the source requirement from which they were derived are tabulated in Table II-7 to provide traceability. Many requirements appear in more than one source document and only the primary source is listed in the summary table.

TABLE II-7. DERIVED SYSTEMS REQUIREMENTS SUMMARY

SOURCE REQUIREMENT	DERIVED REQUIREMENT	PRIMARY SOURCE
The Tug Will be Active Element in Providing the Following Services to Passive Spacecraft in the Mission Model: • Retrieval and Retrun to Earth • Servicing	The Rendezvous / Docking System Shall Accommodate Variations in Spacecraft Weights, c.g. and Size Variations for Delivery of One Spacecraft or Set and Retrieval of Another S/C or Set The Rendezvous / Docking System Shall Not Interfere With Servicing of Spacecraft	Tug Rqmt's MSFC 68M00093-1 and RFP
The Tug Injection Accuracies Shall be Known Within: • Position - 7.8 km (4.2 nmi) • Velocity - 3.4 m/s (11.3 fps)	The Rendezvous / Docking System Shall be Designed to Accommodate These Variations	Tug Rqmt's MSFC 68M00093-1 Para 3.2.1.2.2.5
The Tug Shall be Capable of Docking With Spacecraft	Docking Misalignments Shall be Removed by the Docking System	GDC Avionics Study
Provisions Shall be Made to Preclude Tug Tank Implosion During Return	Implies Safing Provisions for S/C Shall Also be Provided and Reinforces Umbilical Reconnection	IBM Operations Study (Reference TS-24-10-58)
The Spacecraft State Shall be Known Within the Following: • S/C Position 1.85 km (1 nmi) (3σ) Spherical Radius • S/C Attitude Rate - Controlled Within 17 mr/sec (1 d/s) All Axes	The Rendezvous / Docking System Shall be Designed to Accommodate These Variations in S/C State Intelligence	GDC Avionics Study Report
The Tug Shall Provide Spacecraft Spin / Despin for Deployment / Retrieval Up to 100 RPM	The Docking System Shall Provide Spin / Despin for Deployment and Retrieval of Spacecraft	Tug Rqmt's MSFC 68M00039-1 Para 3.2.1.2.2.3
Tug Plume Impingement Shall Not Irreparably Damage Spacecraft	Rendezvous & Docking Strategy Shall Minimize Plume Impingement	Engineering Judgement
Tug Propellant Slosh or Other Dynamics Effects Shall Not Result in Irreparable Damage to Spacecraft	Docking System Shall Accommodate Dynamic Loads	Engineering Judgement

TABLE II-7. DERIVED SYSTEMS REQUIREMENTS SUMMARY (continued)

SOURCE REQUIREMENT	DERIVED REQUIREMENT	PRIMARY SOURCE
The Tug Shall be Compatible with SGLS or STDN / TDRSS	The Rendezvous / Docking System Shall be Compatible with the Tug Communications System (e.g. -TM, TV)	IBM Operations Study (Reference TGI - 12 - 10 - 15)
The S/C Shall Provide Redline Limits for Mission Rules, Jettison, Hazardous Fluids, Pressurant Dump and System Safing for Abort	The R/D System Shall Enhance Abort Capability, or as a Minimum Shall Not Preclude Abort ∴ UNDOCKING IS A REQUIREMENT	Tug Rqmt's MSFC 68M00039-1 Para 3.2.6.2.4
Provisions Shall Be Made for Remote Emergency Jettisoning of S/C Deploying Equipment as Necessary to Complete Retrieval and Stowage	Jettisoning of Deployment Mechanism Shall Not be Inhibited by R/D System	Tug Rqmt's MSFC 68M00039-1 Para 3.2.6.1.1.u
The Tug Shall Provide for "Infant Mortality" Retrieval of Spacecraft The Tug Shall Provide Post Deployment Visual Inspection to Insure Spacecraft Preparation are Adequate	The Rendezvous / Docking System Shall Permit "Infant Mortality" Retrieval (This Implies S/C Checkout After Release and Before Continuing Mission. Further Implication is Retrieval of S/C Not Scheduled or Designed for Retrieval.)	MDAC Report G5954 and IBM Operations Study (Reference TGI - 10 - 10 - 31)
Provisions Shall be Made for Safing on Command Any Unused S/C Ordnance Prior to Retrieval Capability Shall Exist for Ground Initiation of All Control Signals to the S/C Interface	Implies S/C Safing Prior to Recovery by Tug or Reconnection of Monitor & Control Umbilical	IBM Operations Study (Reference PTI - 33 - 10 - 79 & PTI - 1 - 17 - 140)

TABLE II-7. DERIVED SYSTEMS REQUIREMENTS SUMMARY (continued)

SOURCE REQUIREMENT	DERIVED REQUIREMENT	PRIMARY SOURCE
Safety Critical Data - The Tug Shall Provide Tug / S/C Safety Critical Data During Deployment / Retrieval by Orbiter Verification / Talkbacks - Commands Affecting Safety Critical Equipment Status Must Have Associated Data Transmission to Provide a Positive Functional Verification Data - The Data Link Between Tug and S/C During Any Part of the Mission Shall be by Hardline Only Fluid Interfaces - Propellant Fill, Drain, Dump, Pressurant Fill, Dump and Coolants Safety - The Tug / S/C Shall be Safed Prior to Orbiter Approach - Provision Shall be Made to Confirm All Safety Critical S/C / Tug Interfaces Are Securely Reconnected Prior to Retrieval	The Rendezvous / Docking System Shall Not Interfere With Tug / S/C Service Interfaces (Implies Monitoring and Control Interfaces be Re-established or Spacecraft Safing be Performed Before Retrieval by Tug)	IBM Operations Study and MSFC 68M00039-1 IBM References PTI - 1 - 17 - 140 PTI - 2 - 10 - 70 PTI - 8 - 10 - 20 OTI - 25 - 10 - 19 OTI - 57 - 10 - 70 OTI - 12 - 10 - 70 OTI - 62 - 10 - 75
Capability for Static Discharge Between the Tug and S/C Shall be Provided	The R/D System Shall Incorporate This Requirement, or as a Minimum Not Interfere with the Provisions.	Tug Rqmt's MSFC 68M00093-1 Para 3.2.6.1.4 (d)(9)
The Sturctural Interface Between S/C and Tug Shall Transmit the S/C Loads into the Tug Structure with 25% Margin of Safety Under the Most Adverse Shuttle Design Loads, Excluding Crash Landing	The R/D System Shall Support These Loads	Tug Rqmt's MSFC 68M00039-1 Para 3.2.6.2.3 (b)(9)

TABLE II-7. DERIVED SYSTEMS REQUIREMENTS SUMMARY (continued)

SOURCE REQUIREMENT	DERIVED REQUIREMENT	PRIMARY SOURCE
The Space Tug and S/C Shall be Compatible with All Shuttle Imposed Environment	The R/D System Shall be Compatible with Shuttle Orbiter, Tug and S/C Imposed Environments (e.g., Docking Loads, Landing Loads, etc.)	Tug Rqmt's MSFC 68M00039-1 Para 3.2.7.4.10 & 3.2.7.4.11
All Electrical, Mechanical and Fluid Interface Connections Shall be Fail Safe	The R/D System Interface Connections (Electrical Only) Shall be Fail Safe	IBM Operations Study (References PTI - 14 - 10 - 45 & Safety 36 - 71)
Specified Requirement	R/D System Candidates Shall Include: – Autonomous System – Hybrid System – Manual System – Lo-cost Compromise	RFP

B. SUBSYSTEM REQUIREMENTS BUDGETING

Subsystem requirements, as this section will deal with it, refer specifically to performance requirements on the design characteristics of the sensor and docking mechanism. As all of these parameters are interrelated, the derivation of requirements is really a budgeting process that arrives at the best performing hardware for the lowest weight and cost. The factors in this budgeting are illustrated in Figure II-5.

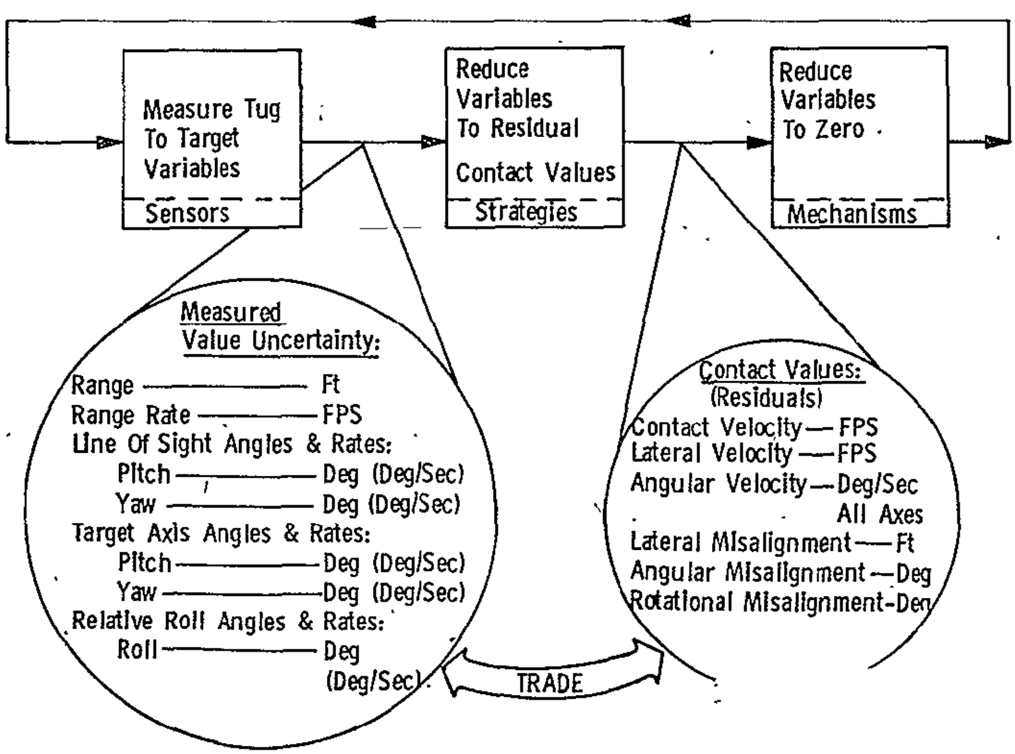


Figure II-5: Docking Budget Issue

Considerations of docking one vehicle to another consist of measuring the relative states of the vehicles, maneuvering to change the states to desired values and finally, securing one vehicle to the other. Errors and uncertainties, of course, complicate these steps. The sensors used to measure the relative states have inherent uncertainties on the measured values. Thus, as maneuvers are performed to complete the rendezvous and docking maneuvers, residual uncertainties result in uncertainties in the vehicle states at contact. Maneuver algorithms and maneuver hardware also have a contribution to the total uncertainty. Therefore, the docking mechanism must have the capability to tolerate the uncertainties resulting from the maneuver and the sensor measurements. Some of the mechanism design parameters that are influenced by the conditions of the vehicles and their mechanism's at docking are illustrated in Figure II-6.

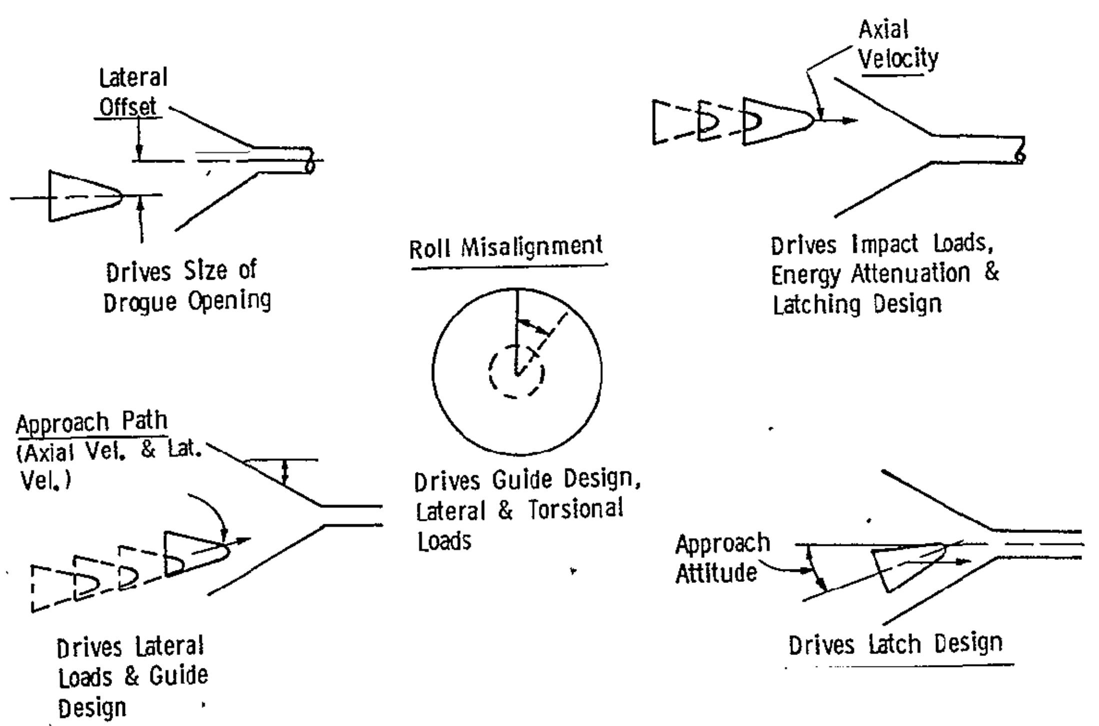


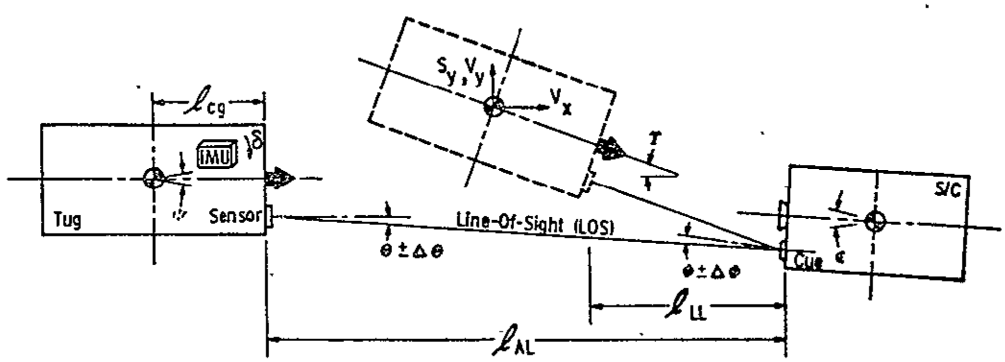
Figure II-6: Docking Mechanism Design Parameters

To arrive at the desired requirements, detailed geometrical conditions at docking were developed for all possible cases. Equations were then written for these conditions that expressed the interrelationships and uncertainties affecting the docking. It was found simplest to write equations for the docking mechanism in terms of the other uncertainties such as Tug and sensor. A specific equation was written for each of the following docking mechanism parameters.

- Angular Misalignment (Impact Docking)
- Angular Misalignment (Non-Impact Docking)
- Lateral Displacement (Impact Docking)
- Lateral Displacement (Non-Impact Docking)
- Lateral Velocity
- Contact Velocity
- Roll Misalignment
- Steerable Probe Maximum Angle (Non-Impact)
- Steerable Probe Maximum Rate (Non-Impact)

An example of the approach is provided in Figure II-7 for the first parameter on the list; angular misalignment. The geometrical assumptions and resulting equations are shown. The equations were coded for computer program solution. A typical plot, for the conditions listed, is shown in Figure II-8. Other parameters can be plotted for any set of values desired. A detailed definition of the other equations listed above is provided in Part A of Section III in Volume IV. The computer program coding for the more complex equations is also provided in that section. A large library of computer plots showing performance of the mechanism and/or sensor and sensitivity to other system parameters was generated. Those curves formed a data base for definition of the desired detail hardware requirements. This detailed derivation is provided in Part B of that same Section III. That section has derived a set of requirements for the following five different configurations:

Manual Impact Docking
Manual Non-Impact Docking
Autonomous Impact Docking
Autonomous Non-Impact Docking
Hybrid Impact Docking



τ_I - Angular Misalignment (Impact Case)
$\Delta\theta$ - LOS Uncertainty
$\Delta\phi$ - Target Attitude Uncertainty
ψ - Tug Deadband
ϵ - S/C Deadband (Or Precession)
δ - IMU Drift
ℓ_{cg} - Tug c.g. To Interface Distance
ℓ_{LL} - Range At Which LOS Data Is Lost
ℓ_{AL} - Range At Which Target Att. Data Is Lost
V_x - Axial Velocity
V_y - Lateral Vehicle (c.g.) Velocity
S_y - Lateral Position Error
ℓ_{SK} - Stationkeeping Distance (Non-Impact).

$$\tau_I = \sqrt{\left[\sin^{-1}\frac{\sqrt{(\ell_{AL}\sin\phi)^2+\left(\frac{V_y\ell_{AL}}{V_x}\right)^2}}{\ell_{cg}+\ell_{LL}}\right]^2+\psi^2+\epsilon^2+\Delta\theta^2+\Delta\phi^2+\left(\frac{\delta\ell_L}{V_x}\right)^2}$$

$$\tau_{NI} = \sqrt{\left[\sin^{-1}\left(\frac{S_y}{\ell_{cg}+\ell_{SK}}\right)\right]^2+\psi^2+\epsilon^2+\Delta\theta^2+\Delta\phi^2}$$

Figure II-7: Angular Misalignment Geometry

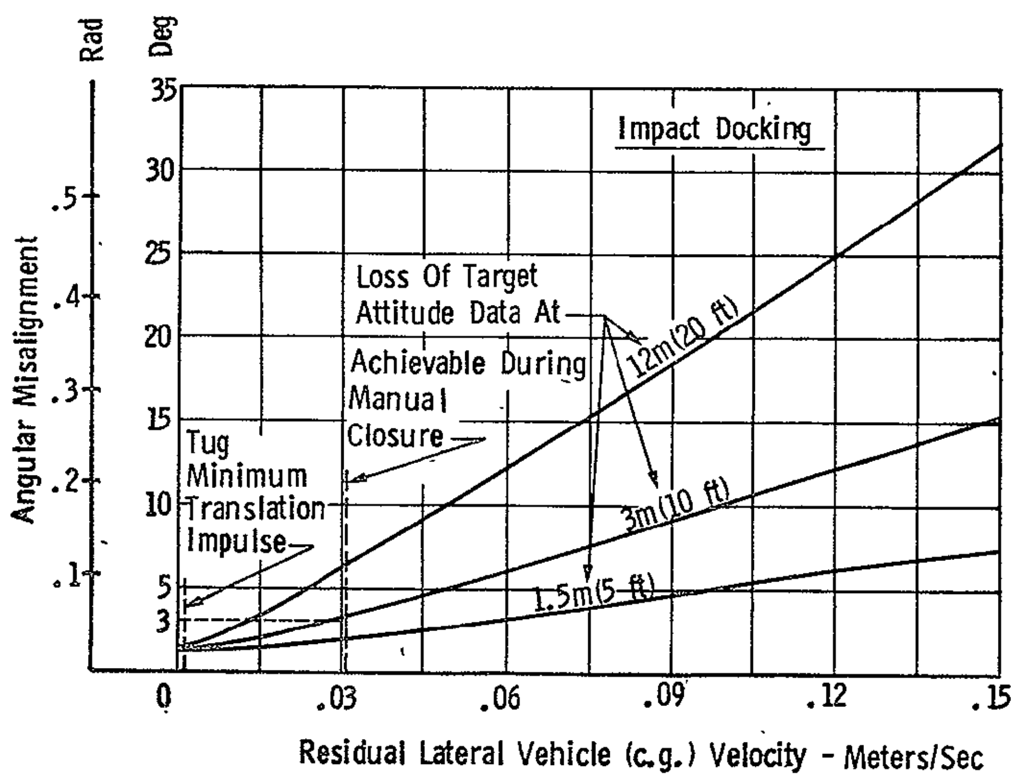


Figure II-8: Angular Misalignment vs Vehicle Lateral Velocity

The derivation in Part B of Section III represented only the first phase of the requirements definition. As was pointed out earlier, the initial definition was based on a set of worst case conditions existing at a single point in time. These worst case errors were then RSS'd in the analysis. To verify that these conclusions were indeed valid and to expand on them where necessary, a dynamic docking simulation program was written that duplicated the docking process under dynamic conditions and in the presence of expected Tug and sensor uncertainties. See Section II-B of this volume for a detailed description. The program is a fast running simulation that permitted a Monte Carlo approach to arriving at the expected values for the same docking mechanism parameters examined on an RSS basis in the first analysis.

A good comparison of results was obtained. Table II-8 shows the results of both of these analyses for just a few of the typical docking mechanism parameters.

Table II-8: Simulation Verification Results - Autonomous Configuration

Docking Mechanism Design Parameter	RSS Error Analysis		Dynamic Simulation (Program DOCK) Results
	Results	Spec	
Angular Misalignment	.05 rad (3°)	.08 rad (4.5°)	.05 rad (3°)
Lateral Misalignment	.05 m (.16 ft)	.10 m (.32 ft)	.03 m (.1 ft)
Lateral Tip Velocity	.006 m/s (.02 Fps)	.3 m/s (.1 Fps)	.05 m/s (.15 Fps)

There is a reasonably good comparison between the first two. The column titled "Specification" incorporates a margin; 26 m rad (1.5°) for the first parameter and a factor of 2 for the second. It's the two "Results" columns that should be compared. Somewhat of a discrepancy exists for the lateral tip velocity. It was assumed in the RSS error analysis that the Tug attitude control would be relatively stable during closing; operating generally in the ACS jet minimum impulse regime. In program DOCK a more unsophisticated, coarser control system was implemented to minimize program run time. This resulted in somewhat larger vehicle deadband rates during closure which, in turn, reflected into higher tip velocities. It is felt the specification of .05 m/s (.1 Fps) is still a reasonable value.

A summary of the final requirements derived in Part B of Section III, using this two-phase approach, is provided in Tables II-9 through -13. Five general categories of requirements are summarized. They are for the:

Ranging Sensor

Video Sensor

Docking Mechanism

Spacecraft Cues

Tug and/or Man-in-the-Loop Control System

Each requirement in the tables is treated individually in Section III of Volume IV accompanying rationale for its selection.

One comment should be made here regarding the last category above - the Tug and man control requirements. In the analysis for this study it was found that a significant contributor to the errors for an impact docking is traceable to the Tug vehicle lateral velocity. For a manual docking that parameter is a function of how well the man can discern the target cue and detect he is drifting off of alignment. It is a nebulous parameter to pin down, but of great importance because of the major contributor to errors that it is. It undoubtedly requires man-in-the-loop simulation. For an autonomous docking, much tighter control of the vehicle can be achieved due to reasonably high accuracy of the attitude determination sensors. There are limits to the sensor, of course, but there are also finite limits on trimming lateral velocities imposed by the Tug vehicle, its control system autopilot design, ACS thrust levels, ACS minimum impulse bits, etc. These must be known and accounted for in a total error analysis.

A similar argument arises for the non-impact docking, only in this case the concern relates to the stationkeeping period. When the retrieval probe is being extended. A translation deadband is being maintained using lateral position sensing and the Tug control system in a manner similar to the familiar attitude control rotational deadband. The rendezvous and docking sensor accuracies are key error sources, of course, but again the Tug inherent control system implementation limitation, and the man's capabilities are equally significant.

The conclusion of all this is that the capabilities of Tug designs and man himself should be carefully evaluated, in simulation if necessary, and finite and credible specifications be placed on the Tug, or any other applicable trans-

TABLE II-9 RANGING SENSOR REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOUS	
	IMPACT	NON-IMPACT	IMPACT	NON-IMPACT
a) Attitude Determination Capability	No	No	Yes	Yes
1) Attitude Determination Maximum Range	N/A	N/A	91m (300 ft)	91m (300 ft)
2) Attitude Determination Minimum Range	N/A	N/A	3m (10 ft)	.9m (3 ft)
3) Attitude Determination Accuracy	N/A	N/A	± 17 mrad (± 1 deg)	± 17 mrad (± 1 deg)
b) Acquisition Range	46 km (25 n mi)	46 km (25 n mi)	46 km (± 25 n mi)	46 km (± 25 n mi)
c) Range Data Minimum	3m (10 ft)	.3m (1 ft)	3m (10 ft)	.9m (3 ft)
d) Range Accuracy -				
Far- .93 km to 93 km (.5 n mi to 50 n mi)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)
Near-3m to .93 km (10 ft to .5 n mi)	± .3m (± 1 ft)	±.15m (± .5 ft)(long term) ±.02m (±.08 ft)(short term)	± .3m (± 1 ft)	± .3m (± 1 ft)
Near-.9m to .93 km (3 ft to 10 ft)	N/A	N/A	N/A	±.15m (±.5 ft)(day-to-day) ±.03m (±.1 ft)(short term)
e) Range Rate Accuracy				
Far- .93 km to 93 km (.5 n mi to 50 n mi)	TBD	TBD	TBD	TBD
Near-3m to .93 km (10 ft to .5 n mi)	± .03 m/s (± .1 fps)	± .03 m/s (± .1 fps)	± .03 m/s (± .1 fps)	± .03 m/s (± .1 fps)
Near-.9m to .93 km (3 ft to 10 ft)	N/A	N/A	N/A	± .003 m/s (± .01 fps)
f) Field-of-View	± .52 rad (± 30 deg)	± .52 rad (± 30 deg)	± .52 rad (± 30 deg)	± .52 rad (± 30 deg)
g) LOS Accuracy (Incl. Misalignments)				
Far- .93 km to 93 km (.5 n mi to 50 n mi)	TBD	TBD		
Near-.3m to .93 km (1 ft to .5 n mi)	± 17 mrad (± 1 deg)	± 17 mrad (± 1 deg)	± 17 mrad (± 1 deg)	± 17 mrad (± 1 deg)
h) LOS Data Minimum	.3m (1 ft)	.3m (1 ft)	.3m (1 ft)	.3m (1 ft)

TABLE II-10 VIDEO/LIGHTING REQUIREMENTS

<u>CAMERA</u>	
Type	2.5 cm (1") Silicon Intensified Target (SIT) Tube
FOV	.35 radian (20 degrees)
Resolution	525 Lines x 430 Pixels, Minimum
Camera Survivability	Look Directly at Sun
Output Bandwidth	4.5 mHz
Dynamic Range	$\approx$ 10,000 to 1
Maximum Length	.3 m (1 ft)
Power	20 Watts (28 VDC), Maximum
Weight	9.0 kg (20 lbs), Maximum
Scan Time	$<$ 1 sec
<u>LIGHTING</u>	
Type	Tungsten Flood Lamp
Maximum Power	600 Watts
Average Power	20 Watts

TABLE II-11 DOCKING MECHANISM REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOUS	
	IMPACT	NON-IMPACT	IMPACT	NON-IMPACT
a) Angular Misalignment	± .08 rad (± 4.5 deg)	± .07 rad (± 4.1 deg) SLR ± .09 rad (± 5.0 deg) RF	± .05 rad (± 2.8 deg)	± .04 rad (± 2.4 deg)
b) Max Lateral Displacement (prior to STEM Contact if non-impact)	± .13 m (± .42 ft)	± .12 m (± .4 ft)	± .1 m (± .32 ft)	± .06 m (± .2 ft)
c) Max Lateral Velocity (at I/F)	± .07 m/s (± .22 ft/sec)	0	± .035 m/s (± .11 ft/sec)	0
d) Max Contact Velocity	.3 ± .03 m/s (1 ± .1 ft/sec)	.005 m/s (.016 ft/sec)	.3 ± .03 m/s (1 ± .1 ft/sec)	.005 m/sec (.016 ft/sec)
e) Roll Misalignment	± .09 rad (± 5.0 deg)	± .09 rad (± 5.0 deg)	± .09 rad (± 5.0 deg)	± .09 rad (± 5.0 deg)
f) Angular Misalignment at Contact(non-impact system)	N/A	± .07 rad (± 4.1 deg)	N/A	± .04 rad (± 2.4 deg)
g) Max Lateral Displacement at Contact (non-impact)	N/A	± 2.5 cm	N/A	± 2.5 cm
h) STEM Articulation Angle	N/A	± .17 rad (± 10 deg) SLR ± .35 rad (± 20 deg) RF	N/A	± .17 rad (± 10 deg)
i) STEM Articulation Rate	N/A	.08 rad/sec (4.6 deg/sec)	N/A	.075 rad/sec (4.4 deg/sec)
j) Max STEM Extension	N/A	1.5 m (5 ft)	N/A	1.5 m (5 ft)
k) STEM Extension Time	N/A	2 minutes	N/A	2 minutes
l) STEM Retraction Time	N/A	10 minutes	N/A	10 minutes

TABLE II-12 CUE REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOUS	
	IMPACT	NON-IMPACT	IMPACT	NON-IMPACT
Visual	Offset "T"	Offset "T"	Offset "T", where TV is required	Offset "T", where TV is required
Ranging Sensor				
SLR (Cooperative)				
Ranging	1 Corner Cube	1 Corner Cube	Spherical reflector coverage	Spherical reflector coverage
Attitude Determination	None	None	Corner reflector pattern	Corner reflector pattern*
SLR (Non-cooperative)				
Ranging	None	None	None	None
Attitude Determination	None	None	Reflective coating	Reflective coating
RF (Cooperative)				
Ranging	1 RF Reflector (.6m(2') diameter)	1 RF Reflector (.6m(2') diameter)	1 RF Reflector (.6m(2') diameter)	1 RF Reflector (.6m(2') diameter)
Attitude Determination	None	None	4 RF Reflectors	4 RF Reflectors
RF (Non-cooperative)				
Ranging	None	None	None	None
Attitude Determination	None	None	4 RF Reflectors	4 RF Reflectors

*Due to limitations on minimum range of $\approx$(3m) of the selected corner reflector pattern, an additional smaller diameter (< .3m) spacecraft cue may be necessary with the GaAs SLR that provides attitude and position data in a rapid fashion, probably requiring a special mode in the SLR for that close-in stationkeeping.

TABLE II-13 MAN AND/OR CONTROL SYSTEM REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOUS	
	IMPACT	NON-IMPACT	IMPACT	NON-IMPACT
a) ACS Minimum Impulse Bit	20 ms	20 ms	20 ms	20 ms
b) Lateral Translation Time Capability	.03 m/sec (.1 ft/sec)	.02 m/sec (.1 ft/sec)	.003 m/sec (.01 ft/sec)	.003 m/sec (.01 ft/sec)
c) Axial Translation Trim Capability	N/A (automatic)	±.0006 m/sec (±.002 ft/sec)	N/A	±.0006 m/sec (±.002 ft/sec)
d) Lateral Translation Deadband	N/A	±.152 m (±.5 ft)	N/A	.03 m (.1 ft)
e) Lateral Translation Deadband Rate	N/A	±.0006 m/sec (±.002 ft/sec)	N/A	±.0006 m/sec (±.002 ft/sec)

portation vehicle, for parameters that relate to rendezvous and docking performance such as translation limit cycles, etc. No such specifications currently exist. Similar finite specifications should be placed on the manned control loop, which includes not only the Tug but the entire imaging loop, ground delays, displays, and others.

One final realm of requirements that is ultimately as important as those discussed thus far is the detail mechanism design requirements that relate to contact energy absorption capability of the mechanism. Specifically, these are requirements for damping, load carrying capabilities, shock absorbers, etc. Quantitative values for these requirements were not developed during this study, but rather, emphasis was placed on refining and verifying the tools that develop these requirements. Our approach and the tools developed are discussed in detail in Section I of this volume. The definition of finite values is dependent on an explicit detailed representation of the mechanism itself. Such definition was not available. In addition, the sophistication of the program incurs program run time costs not in keeping with the preliminary design nature of the rest of the study. The real objective was not so much finite design parameters, but rather verification that a tool exists that can provide those parameters at a time when a firm mechanism choice has been made and detail design is ready to be initiated. That objective was met.

C. COMPONENT CANDIDATES

This part of Section II summarizes the candidate sensors, docking mechanisms, strategies and algorithms that were compiled as a data base from which the candidate systems are configured in Section III.

1. Sensors - The purpose for sensors in the rendezvous and docking system are to provide the following data on the target S/C:

Range
Range Rate
Line-of-Sight Angle
Target Attitude

An initial objective in this study was to canvas all existing or potential sensors that could provide any one of, or all, the data desired. That survey was conducted, vendors were contacted and from that a number of optimum sensors representing several different technologies were selected as the hardware data base from which the candidate manual autonomous and hybrid systems were configured in Section III.

One of the key criteria in the candidate selection process was that the list should represent several different feasible technologies, specifically some proven and some advanced. It should also include some high performing sensors as well as some lower performing but inexpensive units. Each sensor did not have to provide all the data desired; however, where only some data was achievable, other alternative methods of arriving at the remaining data had to be available before this sensor could be considered a valid candidate.

A list of the final set of sensor candidates is provided in Table II-14, along with a summary of the rationale for selection. Each of those shown are discussed in more detail below.

Table II-14 Sensor Hardware Candidates

Subsystem	Candidate	Rationale
Sensors		
Laser Radars	o Ga As	o Current Tug Baseline
	o CO_2 Cooperative	o Long Range Capability
	o CO_2 Non-Cooperative	o Minimize S/C Cues
TV	o Silicon Vidicon	o Shuttle Development
RF Radars	o Modified Apollo Rendezvous - Non-Cooperative	o Flight Proven, Minimum S/C Impact
	o Modified Apollo Rendezvous - Cooperative	o Lower Weight and Power
	o Dual Mode - Non-Cooperative (Rendezvous Radar above plus Short Range Pulse System)	o Single Unit, Full Range Capability, Minimized S/C Impact
	o Dual Mode - Cooperative	o Lower Power and Weight than above

a. Scanning Laser Radars - The first one discussed, the GaAs SLR, has been under development for several years. The design is feasible and a number of performance capabilities have been demonstrated in test. No qualification testing has been conducted.

A number of studies has been published by the original developer, ITT, San Fernando, California. They are references

The GaAs SLR is currently baselined as the rendezvous and docking sensor in the spare Tug Avionics Definition Study (Reference 2) dated April 1975.

The GaAs SLR is a line-of-sight acquisition and tracking system that will determine the relative location of a target by measuring the line-of-sight range to the target, and the pitch and yaw line-of-sight angles. The range rate and angle rates are determined by differentiating the range and angle measurements.

Target attitude is derived by computation onboard utilizing reflected laser pulses from several reflectors mounted in a known orientation on the vehicle. A block diagram of the device is depicted for a single target in Figure II-9.

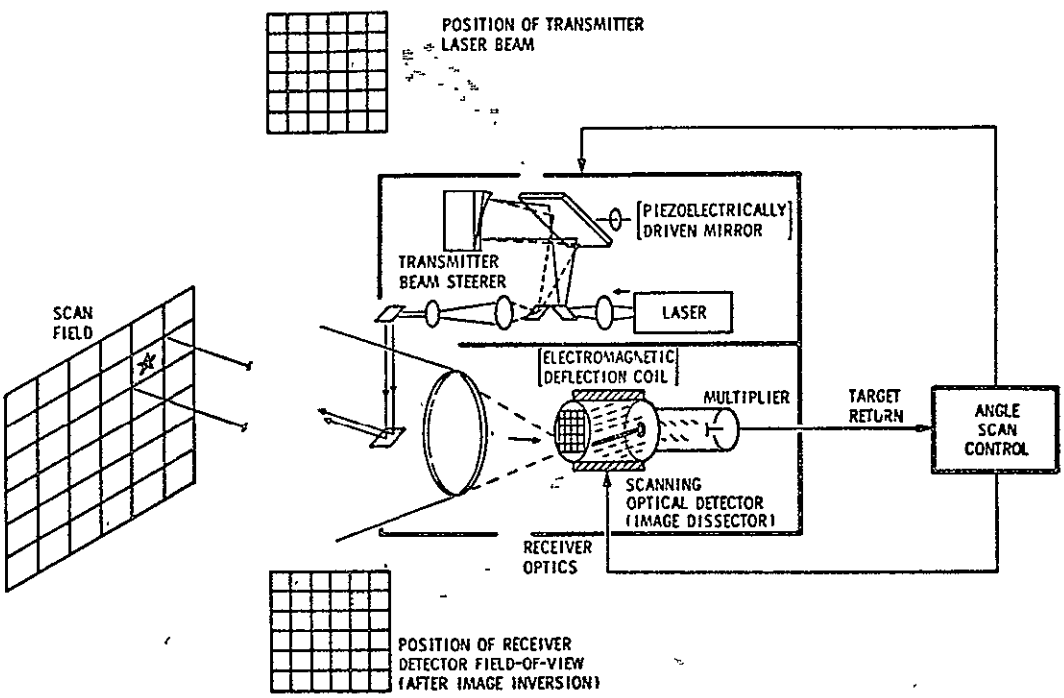


Figure II-9 GaAs Scanning Laser Radar

The SLR is employed in a cooperative passive application on the Tug; that is, no active electronics are required on the target, but some passive reflective device, such as a mirror, is necessary. In fact, an array of corner cube retroreflectors is require to permit acquisition and tracking at a maximum range of 46 Km (25 n mi). Four additional corner cube retroreflectors, in a "T" configuration, are required for the docking phase.

Some pertinent parameters of the GaAs SLR are summarized in the first column of Table II-15.

Table II-15 SLR Candidates Characteristics Summary

Sensor	GaAs	CO_2
Type	Pulsed	Pulsed
Wavelength	9 Microns	10.6 Microns
Mode	Cooperative Passive	Non-Cooperative
Mechanization	Beam Steerer/Vidicon	Oscillating Mirror
Peak Power	2 Watts	1.2K Watts
PRF	1/10K Hz	100K Hz
Beamwidth	1.7 m rad x 1.7 m rad ($0.1^\circ \times 0.1^\circ$)	$0.01^\circ \times 0.01^\circ$
FOV (Max)	.5 rad x .5 rad ($30^\circ \times 30^\circ$)	$30^\circ \times 30^\circ$
Frame Time (Acq)	140/14 Sec	360 Sec
Range Accuracy	.1 m (0.33 Ft)	.1 m (0.33 Ft)
Acquisition Range	46 Km (25 n mi)	46 Km (25 n mi) ($P_d = 0.99$)
Pulse Width	70 n sec	350 n sec
Pulse Rise Time	20 n sec	TBD
Minimum Range	~ .3 m (1 Ft) Possible	~ .3 m (1 Ft) Possible
Average Power	0.14 m Watts	40 Watts
Weight	18 Kg (40 Pounds)	22.6 Kg (50 Pounds)
Input Power	40 Watts	200 Watts 100 Watts (Cooperative)
Estimated MTBF	7000 Hours	2000 Hours
Technology	Present	Present
Target Vehicle Aid	16 Corner Cubes (Rend) T Configuration (Docking)	None
Development Status	Prototype	Paper Design

b. CO_2 Laser Radar - The CO_2 laser, under recent development by Norden Division of United Aircraft for MSFC, is not as far along as the GaAs SLR, but has certain unique advantages that justify its inclusion as a viable candidate for Tug rendezvous and docking. Principal among these is a capability for skin track ranging at relatively long ranges. Thus, the impact on the S/C is minimized,

a feature the GaAs cannot achieve with its power limitations. Both a cooperative, as well as a non-cooperative version of the CO_2 laser, was considered since the cooperative version has a lower weight and power. However, the CO_2 laser's real advantage is in the non-cooperative mode.

The sensor described herein is configured to utilize a passively Q-switched CO_2 laser as the transmitter active element, and a four-quadrant photodiode array, operated as a coherent receiver element in a heterodyne mode. The aperture is about 15 cm (3 inches), and the telescope steers the beam in a .7 rad x .7 rad (40^o x 40^o) window. The laser, as well as the receiver configuration, are similar to equipment for tactical airborne applications. The electronics, logic, and computer interface are similar to equipment that is associated with most coherent pulse doppler radar sets.

A block diagram of the system is provided in Figure II-10 with an artist's concept of the device in Figure II-11.

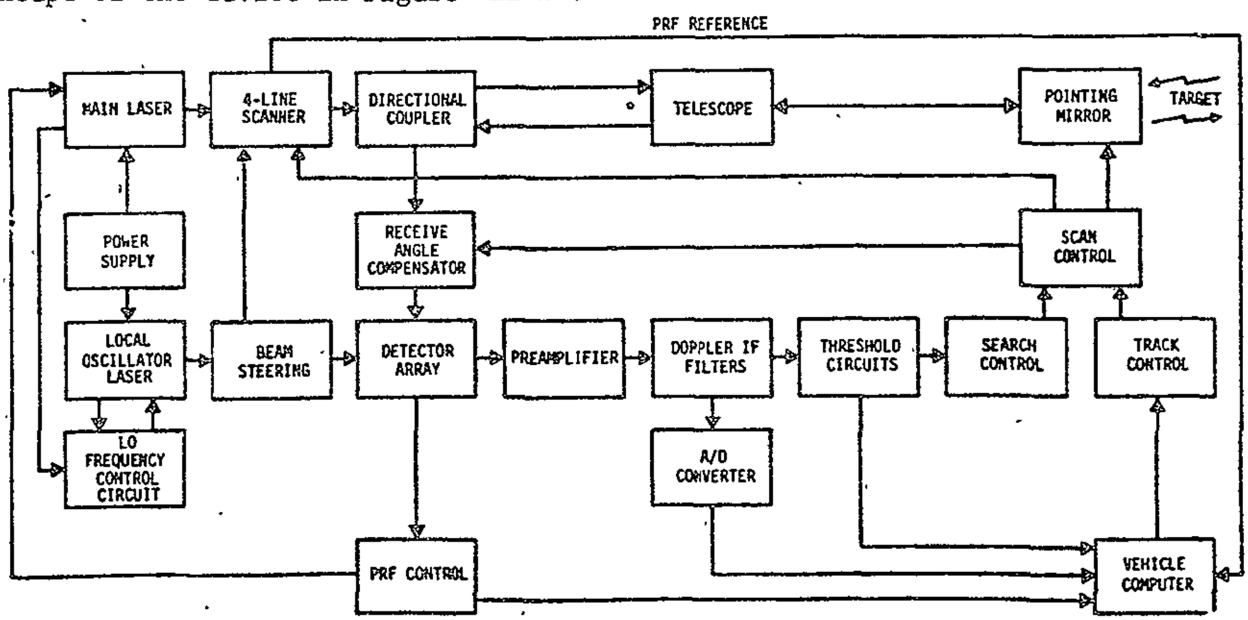


Figure II-10 CO_2 Laser Radar Block Diagram

Pertinent performance characteristics are summarized in Table II-15.

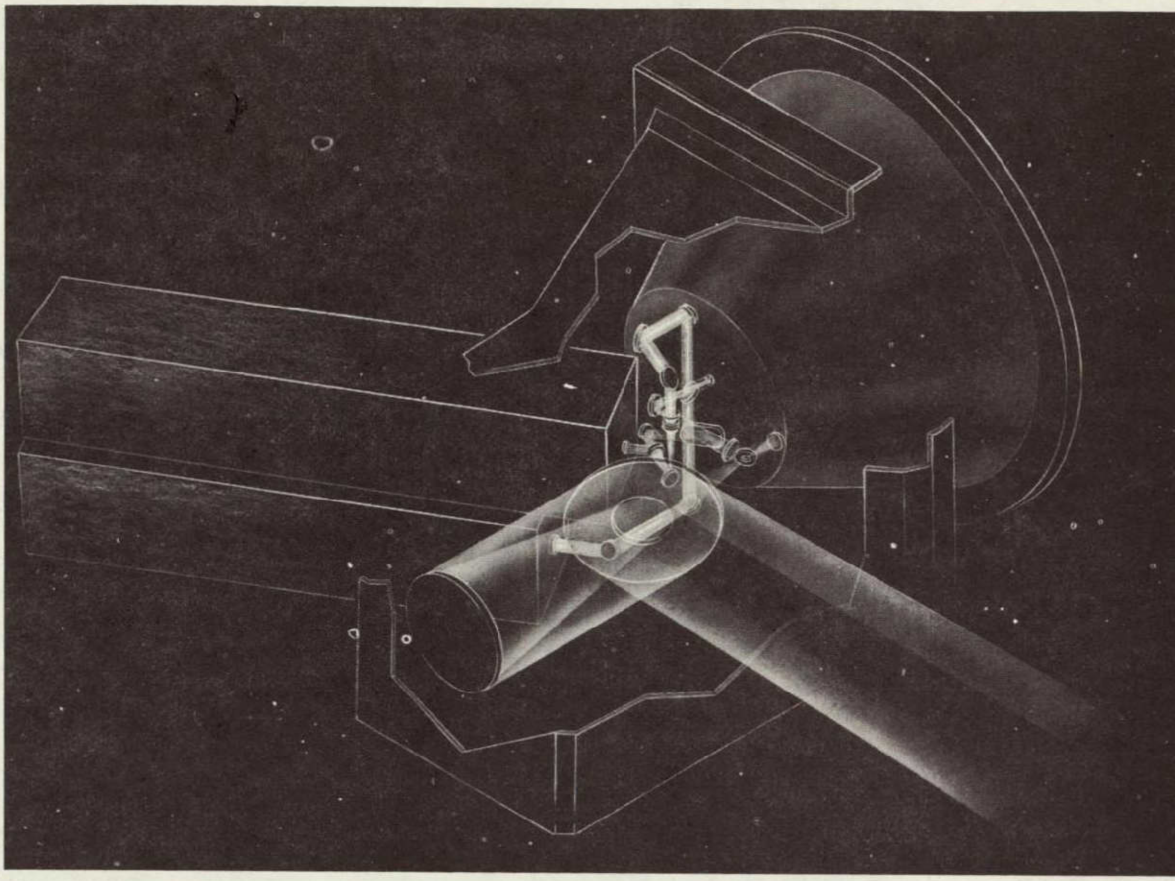


Figure II-11 CO_2 Laser - Artist's Concept

c. Video Sensor - Identification of requirements, summarized earlier in Table II-10, and discussed in more detail in Part B of Section VI, Volume IV, indicate that use of the TV camera to be developed for the Shuttle program is feasible for Tug application. Some modification may be necessary but, in general, the assumption that much of the initial development will be borne by Shuttle appears valid. There is still further definition of requirements for the Shuttle camera anticipated, but the general characteristics that Shuttle is looking for

are shown in Table II-16. No particular vendor is selected at this time, pending the Shuttle selection next year.

The Shuttle camera described in Table II-16 with its high scan rate, will require some storage and buffering on the Tug to be compatible with the communication downlink bit rate of 50 KBS, as opposed to the Low Light Level TV in the current Avionics baseline.

The Shuttle program is not certain whether an intensified tube will be required or not. RCA, a potential bidder, does not think so; but for Tug application it has been assumed this will be a necessity since image data at 30 m (100') will be necessary. Lighting is also an assumed requirement due to possible need for target cue recognition in the dark. The cue may be set back in the docking port as well. Strobe lighting will be assumed since picture rates on the ground will be at a relatively low rate. For more autonomous operation, requiring onboard algorithms deriving range, range rate, LOS, or target attitude, the picture speed would undoubtedly be higher and the strobe rate higher, but continuous lighting does not appear to be a requirement for unmanned application.

Table II-16 Shuttle TV Candidate Characteristics Summary

Type	2.5 cm (1") Silicon Vidicon Tube
FOV	.35 rad (20^{o})
Resolution	525 Lines x 430 Pixels
Camera Survivability	Look Directly at Sun
Output Bandwidth	4.5m Hz
Dynamic Range	~10,000 to 1
Target Illumination Required	.46 to .92 Lux (5 - 10-Ft Candles)
Maximum Length	.3 m (1 ft)
Power	15 Watts, 28V d.c.
Weight	6.7 Kg (15 lbs)
Image Scan Rate	30 Times/Sec
Lighting	Tungsten Flood Lamps
Development Status	Shuttle TV Camera Development Appears Applicable. RFP in Spring 1976; ATP in 11/76

Additional detailed discussion regarding requirements and support of the above selection is provided in Part B of Section VI in Volume IV. More details on the lighting system required is also presented in that supplement.

Another subject unique to the video system and also discussed in some detail in that section, is the development of software algorithms that are required to process image data into the range, range rate, LOS and S/C target attitude data necessary for rendezvous. Not all that data is necessary for all candidate system concepts. In some cases the processing is done onboard and in others on the ground; however, there is in all cases some form of large data processing required. Some feasibility study and testing has been done at MMC in this area. The approach and some results are provided in that same Part B, Section VI of Volume IV. Illustration of a technique that can calculate centroids, or centers of a S/C for LOS data, and can measure maximum diameter on a repetitive basis for range and range rate data, is provided. It provides significant enhancement of imaging data and further development of this capability is encouraged.

There is also some feasibility study results of data compression techniques presented in that same section. Data compression was recommended earlier as an area of pursuit that would enhance the ground control of the vehicle in manual configurations by speeding up the current quite slow picture update rate on the ground (due to Tug downlink data rate constraints).

d. RF Radars - Conventional RF radar, though not strongly considered for Tug in recent studies, still have some unique capabilities and advantages that place it as a definite contender as a rendezvous and docking sensor. Previously developed radars, such as Apollo LM, provide the required data down to a range of $\sim$30 m to 90 m ($\sim$ 100' to 300'). From that point on in and in order to provide target attitude information, a different concept and design is required. Consequently the survey of potential radars fall into two categories. For the far-out ranging, a number of developed designs were considered, while the close-in data gathering required some new design effort to define a concept that would meet the rendezvous and docking requirements. Some of the candidates surveyed, the derivation of requirements and a detailed description of the final candidates selected is provided in Part A of Section VI in Volume IV, "Supplemental Sensor Analysis". A

brief description of the selected RF subsystems is provided below. As noted in Table II-14 earlier, four systems were selected for the candidate list, but note that two of the four are merely cooperative versions of the other two non-cooperative systems. Both types were evaluated because of the reduced weight and power of the cooperative systems. But, in effect, there are only two different types; referred to as a rendezvous radar, which is useful only up to 30 m (100') of the target, and a Dual Mode radar which incorporates a close-in data gathering capability along with the rendezvous radar above. The latter is comparable to the SLR in the ranges over which it performs and the type of data gathered. The pertinent characteristics of four radars are summarized in Table II-17.

Rendezvous Radar - This unit is a derivative of the Apollo LM rendezvous radar. A design similar to Tug needs is being defined for the Shuttle program. It is presumed much of any development required will have been accomplished on the Shuttle program. Consequently, a major advantage of this unit is the minimal development costs and low risk associated with a flight proven design.

The radar is a pulsed doppler X-band radar with a .9 m (3-foot) casegrain antenna. It will provide a probability of detection (P_d) of .99 on a S/C cross-section of 10 m^2. Acquisition time at 46 Km (25 n mi) is less than 6 seconds. The radar design employs a frequency diversity implementation utilizing five frequencies spaced 50 MHz apart at X-band. This reduces the radar power requirements and improves the target radar cross-section of the complex target vehicles considered for the space Tug mission.

The cooperative version requires a trihedral, triangular corner reflector .24 m (.8' on a side) on the target vehicle. In other respects, it is the same except for the expected reduction in power required and correspondingly in the weight as well.

Dual Mode Radar - The dual mode radar incorporates the rendezvous radar above, both the cooperative and non-cooperative, with a close-

in radar that is essentially new design. It is cooperative in all versions. It utilizes four small RF retroflectors on the target S/C which support the determination of range, range rate, LOS and target attitude determination down to 1 m (3'). A 9 μsec transmitted pulse width is employed for this phase and a wide band receiver is utilized to provide the required high range measurement accuracy. As stated earlier, this close-in capability is a new design, however, it has the advantage of using existing technology hardware. Some predevelopment effort should be expended in this area to develop an alternative to the laser radar techniques.

Sensors	Rendezvous Radar		Dual Mode Radar (Rendezvous Plus Docking)	
	Noncooperative	Cooperative	Noncooperative Rendezvous	Cooperative
Type Frequency Angle Tracking Peak Power	Non-Coherent Pulse-Doppler X-Band Ampl Comp Monopulse 42K W	Non-Coherent Pulse-Doppler X-Band Ampl Comp Monopulse 10K W	Non-Coherent Pulse-Doppler X-Band Ampl Or Phase Comp Monopulse 42K W Rendezvous Mode 10 W Docking Mode	Non-Coherent Pulse-Doppler X-Band Ampl Or Phase Comp Monopulse 10K W Rendezvous Mode 10 W Docking Mode
PRF Beamwidth Search Volume Antenna	1.6K Hz .04 Rad (2.3°) .52 Rad X .52 Rad (30 X 30°) Cassegrain Dual Ref	1.6K Hz .04 Rad (2.3°) .52 Rad X .52 Rad (30 X 30°) Cassegrain Dual Ref	1.6K Hz .04 Rad (2.3°) Rend .52 Rad (30°) Docking .52 Rad X .52 Rad (30 X 30°) Cassegrain (Rendezvous); 4 Horn Mono-pulse Array (Docking)	1.6K Hz .04 Rad (2.3°) Rend .52 Rad (30°) Docking .52 Rad X .52 Rad (30 X 30°) Cassegrain (Rendezvous); 4 Horn Mono-pulse Array (Docking)
Pulsewidth Ant Polarization Receiver B W Target Vehicle Aids	1 μ sec Circular 1.4M Hz None	1 μ sec Circular 1.4M Hz Trihedral, Triangular Corner Reflector, .24M (.8') On a Side	9.0 μsec (Time Shared Receive Mode) Circular (Rendezvous) Linear (Docking) 1.4M Hz None (Rendezvous); Passive Ant With Delay Line (Docking)	9.0 μsec (Time Shared Receive Mode) Circular (Rendezvous) Linear (Docking) 1.4M Hz Trihedral, Triangular Corner Reflector (Rendezvous); Passive Ant. With Delay Line (Docking)
Input Power Maximum Range Minimum Range Estimated MTBF	275 Watts 46 Km (25 n mi) 30M (100 ft) 2000 Hours	120 Watts 46 Km (25 n mi) 30M (100 ft) 2000 Hours	275 Watts (Max) (Rendezvous) 20 Watts (Docking) 46 Km (25 n mi) .6 M (2 ft) (Delay in Tracking Aid) 2000 Hours	120 Watts (Max.) (Rendezvous) 20 Watts (Docking) 46 Km (25 n mi) .6M (2 ft) (Delay in Tracking Aid) 2000 Hours
Technology Development Weight	Present Complete 34 Kg (75 Pounds)	Present Complete 33 Kg (72 Pounds)	Present Rendezvous - Complete; Docking - Paper Design 36 Kg (80 Pounds)	Present Rendezvous - Complete; Docking - Paper Design 34 Kg (75 Pounds)

Table II-17 RF Candidate Configuration Summary

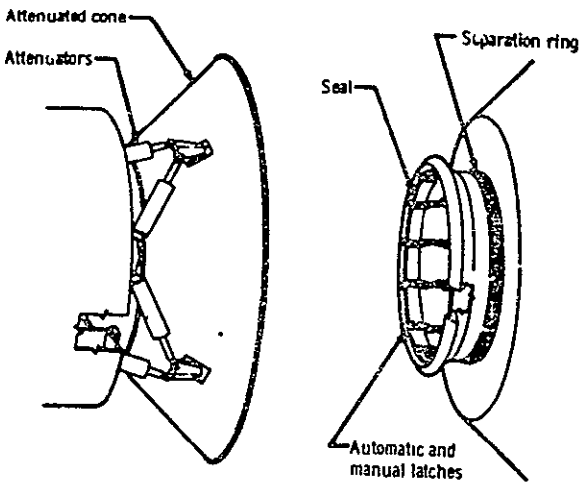
2. <u>Docking Mechanisms</u> - The U.S. space programs' experience with joining two vehicles together in orbit began with the Gemini Program, continued with Apollo and ASTP (Figure II-12). All three used impact mechanisms, and all three were brought to the point of contact under direct manned control. By virtue of being impact systems, all used a system of springs and shock absorbers to reduce shock loads on the mating spacecraft. By virtue of being manned, all were built around provisions for manned ingress/egress; two were periferal mechanisms around a tunnel, and one was a central device which was removed from the tunnel.

While the manned transfer problem is eliminated for the space Tug operation, most other requirements remain and some new and stringent ones appear. The most significant requirements are:

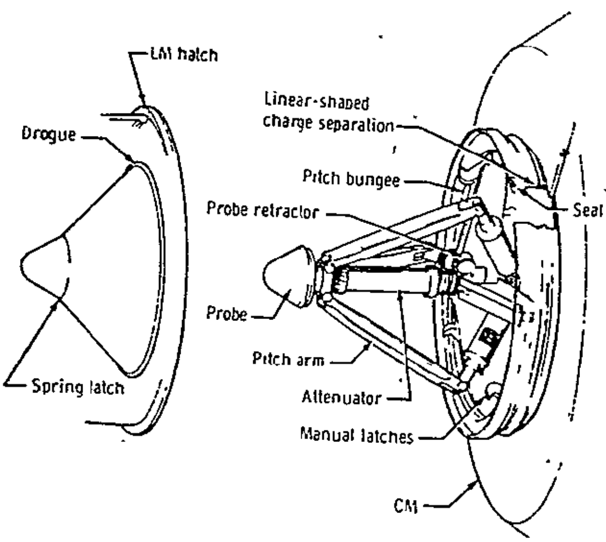
1) Provide support structure to cantilever S/C off Tug in both Tug and Shuttle flight regimes;
2) Provide a delivery/retrieval system capable of delivering up to three S/C and retrieving one;
3) Retrieval interface must be able to accommodate delivery of one diameter payload and retrieval of another;
4) Eliminate final misalignment between vehicles to align docking interface;
5) Deploy or retrieve S/C spinning with rates up to 100 rpm;
6) Provide a redocking capability;
7) Cause minimum impact on retrieved spacecraft design;
8) Minimize weight to minimize Tug payload.

A wide variety of docking mechanism concepts were evaluated (Volume IV, Supporting Analyses). Three basic concepts were found to be most promising and were included in the array of subsystems carried into the systems synthesis activity.

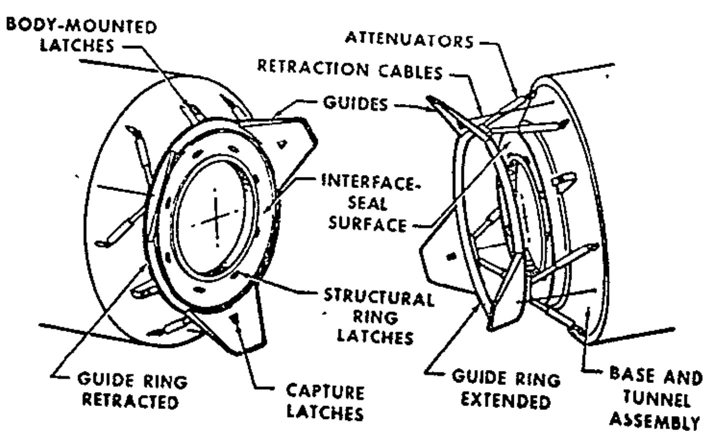
<u>MDAC Square Frame</u>: This approach (Figure II-13) meets the myriad requirements placed on the design with a structurally efficient new design featuring a variety of moderately complex mechanisms. These include: U-jointed A-frames with integral shock-absorbing capability; variable size square frames; and a set of four spacecraft mounting points that incorporate a docking guide, a latch mechanism, and a spin-up mechanism. This approach places some requirement on



Gemini docking system

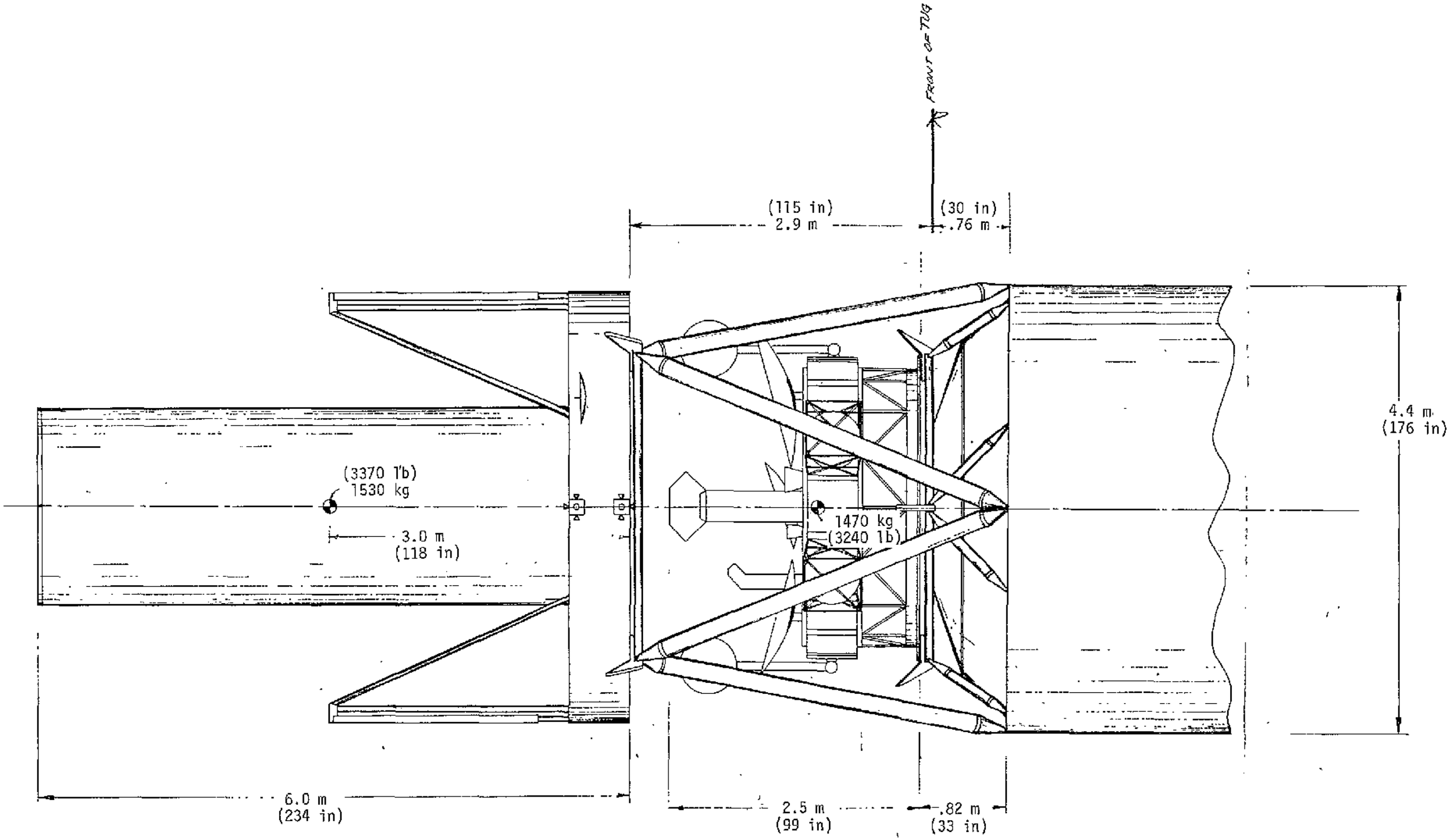


Probe and drogue docking system



ASTP docking mechanism

Figure II-12. Flight Proven Docking Systems



Multiple Payloads - CN-51 (Aft)
EO-59 (Fwd)

Figure II-13 MDAC Docking System

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FOLDOUT FRAME

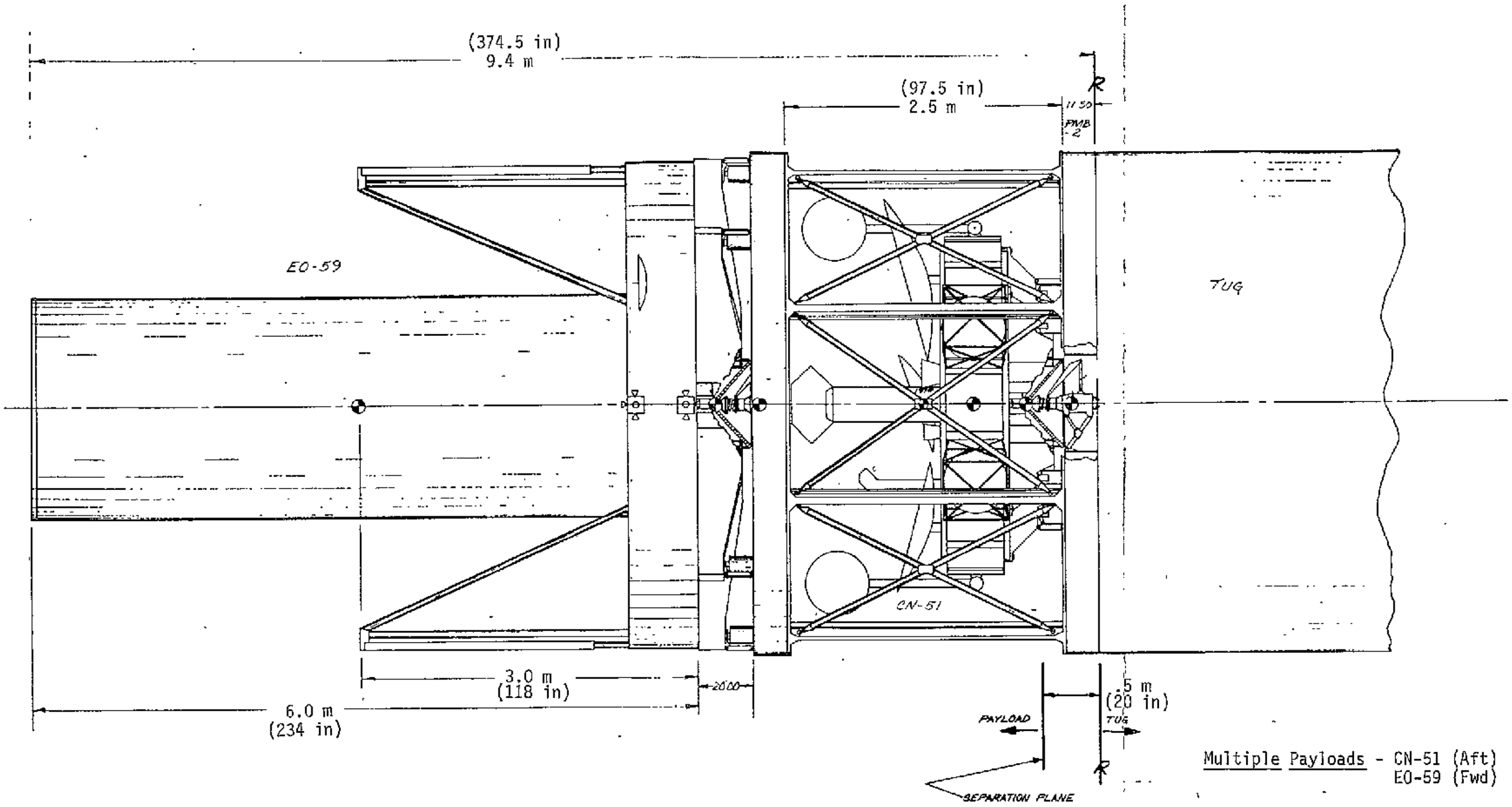
FOLDOUT FRAME

the spacecraft adapter to distribute mounting loads from the four point attachment into whatever structure the spacecraft possesses, and to stablilize the shape of the open square frame. It must generally be rated a sound concept requiring considerable new development.

MMSE Probe/Drogue Beam: This approach (Figure II-14) meets the same array of requirements as the square frame concept using the flight-proven Apollo Probe/Drogue in combination with an array of static structure. In addition, this approach was conceived to meet IUS and Shuttle automated payload requirements. As a consequence, the design has been standardized for a broader application spectrum than is required specifically for Tug applications. It supplies eight hard mounting points for spacecraft of various diameters using a family of spider beams. Structurally, this approach appears heavier than the square frame approach, but it is simpler, uses more existing hardware, and should be less costly to develop. Provision of spin-up capability in the Apollo probe design will be a significant development problem; the spin-up requirement should be carefully assessed before this capability is implemented.

Hybrid Soft Dock System: This approach (Figure II-15), although not as well developed as the previous two, incorporates several desirable features. It achieves soft docking through the use of a steerable, extendable STEM mounted probe (Figure II-16). This probe can be gently inserted in a lightweight spacecraft mounted drogue using man-in-the-loop video concepts. The device then draws the spacecraft back for a soft attachment to a rigid A-frame structure attached to the Tug. The A-frames can be rotated in or out to match spacecraft diameter in a variety of ways; perhaps the preferable approach being an adjustable square frame similar to the MDAC approach. The A-frame structure need not have the variable length shock absorbing struts required for an impact docking. Therefore, the A-frames are rigid, singly hinged panels rather than being constructed from universal-jointed struts. The impact of this system on the spacecraft is minimal, since the drogue device on the spacecraft can be small and light, and since shock loads imparted to the spacecraft will be minimal.

Each of these approaches has some special merit, and some special disadvantage. The square frame approach is light, and has a fair level of development



Multiple Payloads - CN-51 (Aft)
EO-59 (Fwd)

Figure II-14 MMSE Docking System

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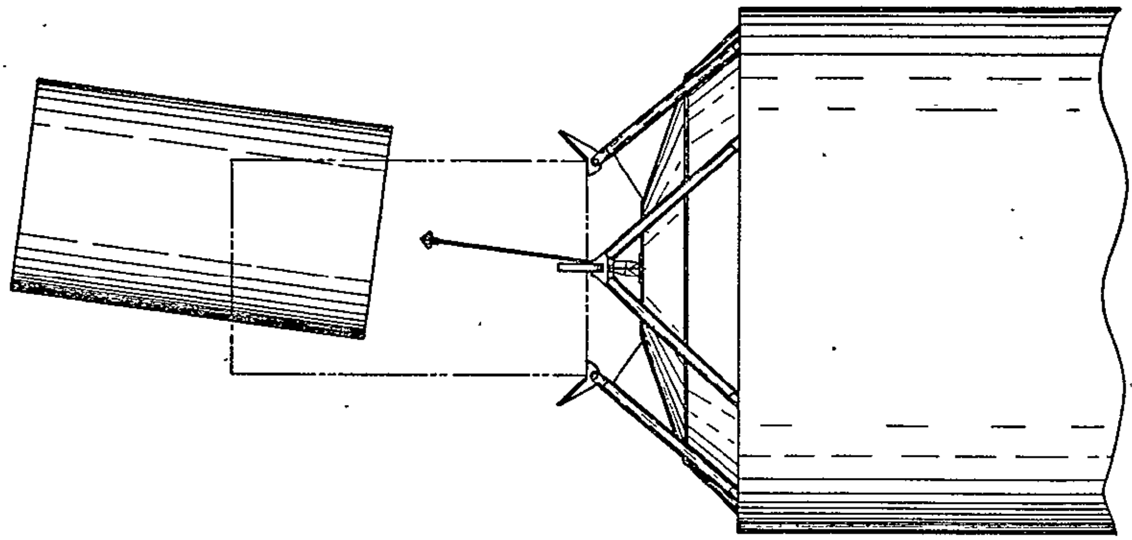

Figure II-15 Hybrid Soft Dock System

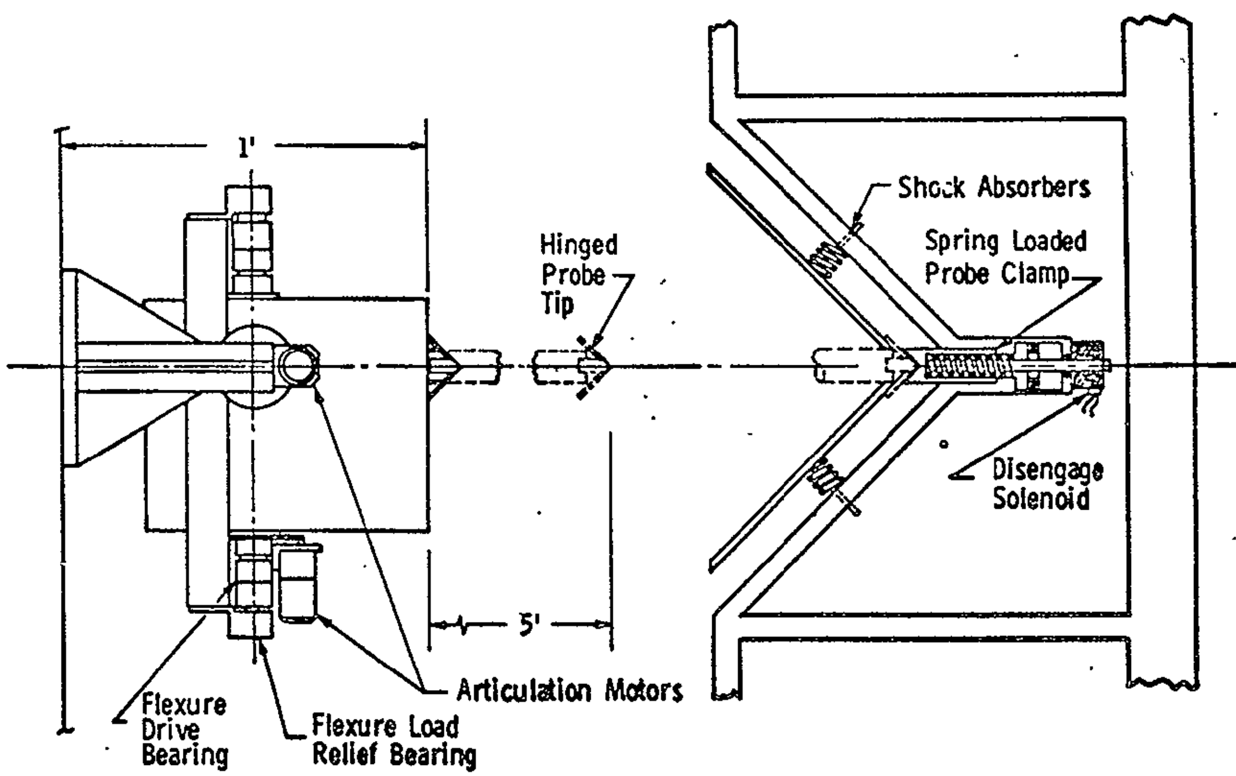

Figure II-16 Steerable STEM Detail

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activity behind it. On the other hand, the structural members involved are complex mechanisms that are not yet qualified. The MMSE approach uses a flight proven docking mechanism, and supports retrieval spacecraft flight loads with a static structure. The approach, however, appears to be quite heavy. The hybrid soft dock approach simplifies the support structure over the MDAC approach and eases the spacecraft impacts at the cost of a complex development in the steerable STEM probe. Comparative weights were developed for these systems for one particular ap lication (structure designed to carry the spacecraft illustrated in Figure II-14 and -15). The comparative weights were: MDAC, 253 kg (556 lbs); MMSE, 441 kg (970 lbs); Hybrid Soft Dock, 241 kg (531 lbs). An added disadvantage cited for the Hybrid Soft Dock System was a high level of risk involved in developing an autonomous docking capability.

3. Strategies - Strategies are the concepts used to meet functional requirements; the methods by which rendezvous, inspection, alignment and docking are to be accomplished. When strategies are combined with the requirements of a desired autonomy level and the requirements of particular sensors (Figure II-17) it becomes possible to define implementation algorithms that will effect the strategy in a computer. These algorithms divide into decision, maneuver, sensor utilization and redundancy management algorithms.

Rendezvous Phase - The first rendezvous task is acquisition of the target spacecraft. In the scenario developed for Tug, this will be accomplished at a nominal range of 23 km (12.5 nm) by searching the $\pi/6$ radians (30°) total field of view where the S/C is anticipated to be. This procedure will depend on the sensor mechanization, but will be straightforward in any case.

Several candidate techniques for rendezvous approach have been suggested in the past (Figure II-18), but two have received the most attention. One of these is a mechanization of Lambert's Theorem which is generally suitable for the direction of precise orbital maneuvers intended to efficiently reach the immediate vicinity of the target spacecraft. With the highly accurate Tug navigation system anticipated, this type of maneuver is considered to be unnecessary for this application. The proportional navigation approach, where line-of-sight rates are nulled and the Tug is constrained to follow a prescribed range/range

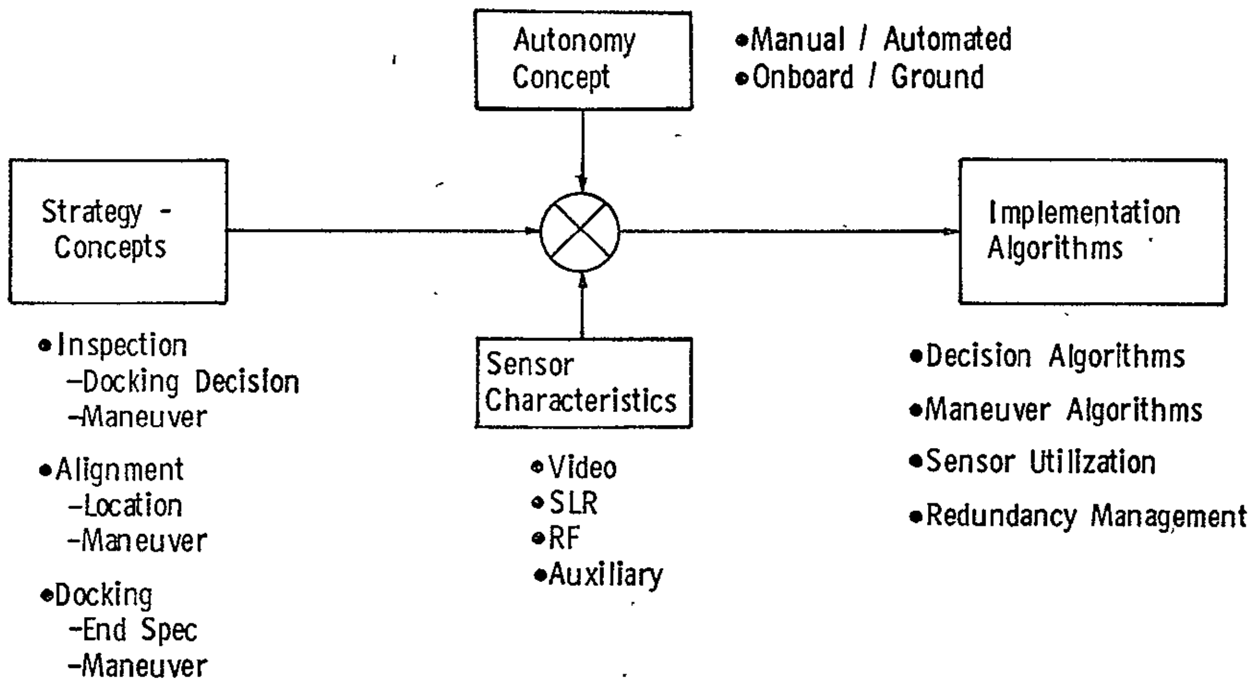


Figure II-17 Operational Strategies Lead to Implementation Algorithms

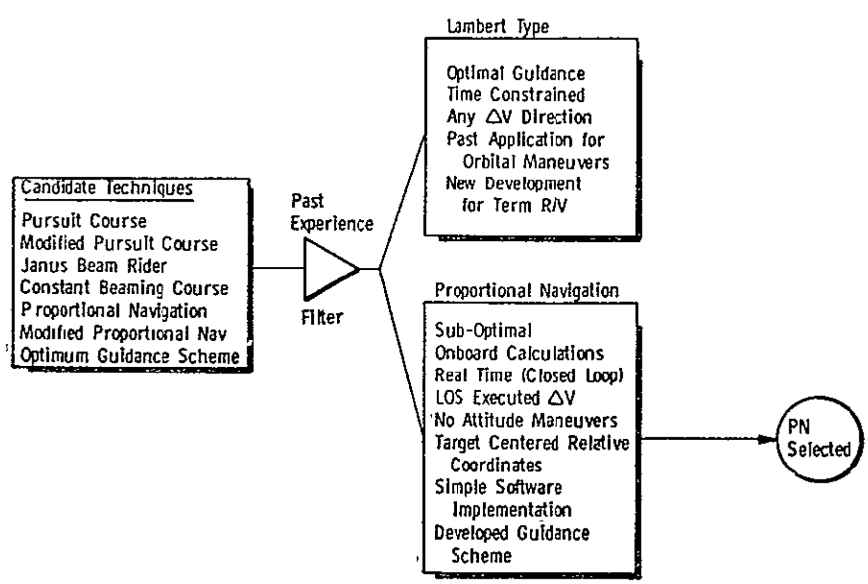


Figure II-18 Rendezvous Strategy Selection

rate approach profile is considered appropriate. Studies described in more detail in Section II.D of this report volume have shown this to be an efficient recommendation with a desirable insensitivity to sensor errors.

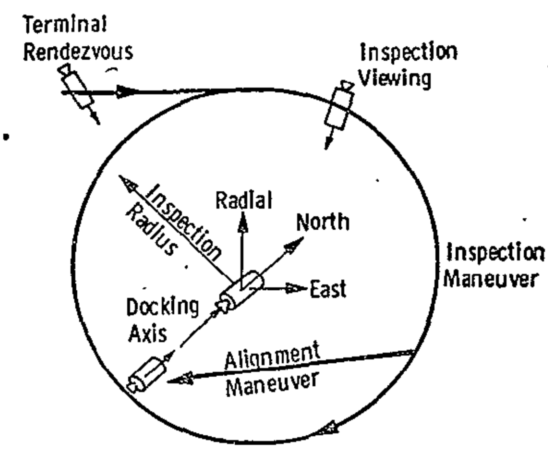
Inspection Phase - The objectives of the inspection phase are to verify the spacecraft ready for docking and to locate and maneuver to the docking axis. A circular inspection maneuver is suggested where the Tug is controlled to always point toward the spacecraft so forward pointing sensors can be used. A near circular orbit (100-ft range, 20-minute period) around the spacecraft is

Objectives
- Verify S/C Ready for Docking
- Locate & Maneuver to Docking Axis

Stepped Circular Inspection Maneuver Selected
- Maintain Tug / Inspection Sensor LOS Towards S/C, Use Propulsion To Maintain Proximity
- Near Circular Orbit @ 50-100ft, 15 Min Period
  - Close Enough for Resolution
  - Balance Between Time & Fuel Required

Anomalous Condition Determination Key Issue
- Concerned with Locally Gathered Data
- S/C Attitude State that could Prevent Docking
- S/C Mechanical Condition, Similar Effect

Alignment Maneuver
- Baseline: Align LOS with Known Inertial Orientation
- Possible Alternate: Use Physical Cues to Direct Maneuver



Algorithm Types Required
- Inspection Maneuver
- Inspection Sensed Data Interpreter
- Docking Axis Locator
- Alignment Maneuver

Figure II-19. Inspection Phase Strategy

recommended. Propellant consumption goes up linearly as range increases (4.5 kg (10 lbs) at r = 15 m (50 ft) vs 9 kg (20 lbs) at 30 m (100 ft) for a 20-minute orbit period). Orbital period, or time for a circumnavigation, also increases propellant consumption nearly linearly as the time per orbit decreases (8 kg (18 lbs) for a 20-minute orbit vs 15 kg (34 lbs) for a 10-minute orbit at a

range of 100 ft (30 m)). An inspection period over 20 minutes long appears to be excessive from an operations standpoint. Therefore, 20 minutes was selected to keep ACS propellant usage to a minimum. The lateral control system using the rate gyros and lateral APS engines could be commanded to produce a constant LOS rate during this phase. The axial control system using axial APS engines can keep the Tug at a constant range. This phase should be initiated on a range criteria to provide a smooth transition from the rendezvous approach phase.

The spacecraft attitude change in state (tumbling, spin rate, wrong attitude, etc.) mechanical condition (broken booms, solar panel not deployed, etc.) and locally gathered data can be used to determine spacecraft condition and commit to dock.

When the docking axis orientation is known the Tug can maneuver to the docking port using commands executed in relative (radial) coordinates. When the docking axis orientation is not known physical cues such as spacing of corner reflectors, size of corner reflectors, RF side lobe control, etc., will be used.

Alignment Phase - The orientation of the spacecraft docking axis in inertial space will generally be known before launch. After the inspection activity is completed, the maneuver to the docking axis can be effected as indicated in Figure II-20. The cross-product of the LOS vector and the docking

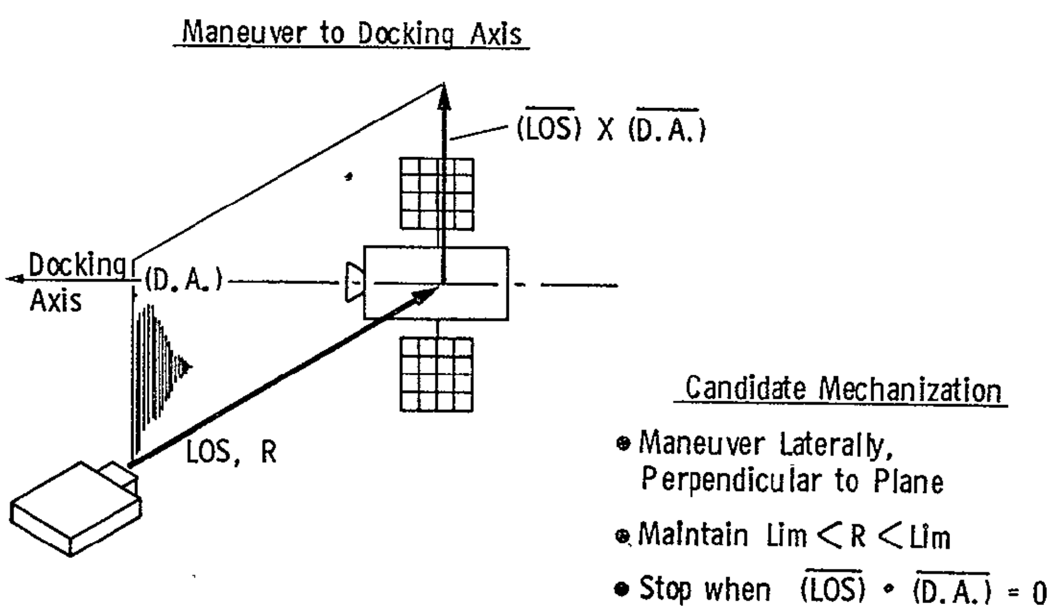


Figure II-20. Alignment Maneuver

axis vector is formed in the Tug computer. Rotation of the LOS vector about this cross-product vector at a constant range is commanded by appropriate instructions to the Tug RCS thrusters. The maneuver is completed when the magnitude of the cross-product vector has been driven to zero.

In the event that the docking axis location is not known before launch, a means of establishing it must be provided. One technique is to use an array of retroreflectors on the target spacecraft as illustrated in Figure II-21.

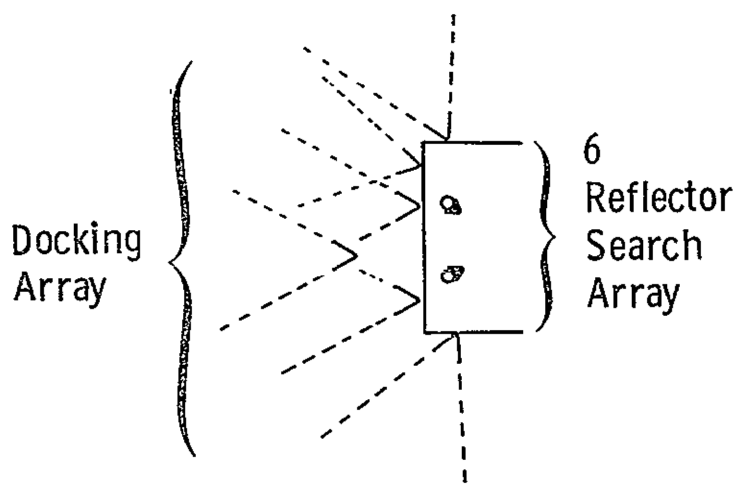
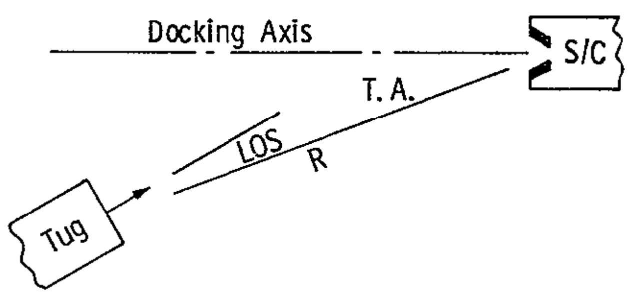


Figure II-21. Docking Axis Location

The approximate location of the docking port can be established after one orbit of the spacecraft with this array. The technique involves remembering where in the orbit cues are visible, how long they are visible, and deriving from this where the pattern centroid is located.

Docking Phase - In an impact docking, the suggested docking closure maneuver would be executed to close in the LOS direction with a constant velocity ($\dot{R}$) when aligned with the docking axis. The axial control system controls the axial acceleration to keep the relative range rate within tolerance. The IMU gyro and accelerometer data can be used in case of data dropout from the rendezvous sensor.

In a non-impact docking, the range rate is commanded to zero as the range is reduced in some range vs range rate profile to achieve a stationkeeping position or a very small impact velocity. Accurate range sensing is essential at close range. Close range measurements of LOS angles and target attitudes are also needed during stationkeeping, which would be mechanized with a phase plane control logic. Vehicle contact would be made with a steerable probe during the stationkeeping mode, and the Tug and spacecraft would be mechanically drawn together.



Impact

- Goal - Drive Down Docking Axis at Constant $\dot{R}$ Until Impact
- Attitude Loop Drives LOS $\rightarrow 0$
- Translation Loop Drives T.A. $\rightarrow 0$
- Periodic $\dot{R}$ Checks to Maintain Within Tolerance
- Combining Relative Data with IMU Data Makes Close-in Sensing Less Critical

Non-Impact

- Goal - Drive Down Docking Axis with $\dot{R} \rightarrow 0$ As $R \rightarrow 0$
- Terminates with Close Proximity Station Keeping or Very Low Velocity Impact
- Close-In Sensing of Range Essential
- Station Keeping Requires Close-In Measurement of LOS, T.A. Also

Figure II-22. Docking Maneuver Candidates

The specific mechanization of these strategies will vary somewhat with the level of autonomy selected, and with the particular sens rs from which measurements will be derived. The level of redundancy, either sensors or back-up control modes, will also influence the specific algorithms to be incorporated into the Tug flight computer. Table II-18 shows the estimates of Tug computer

Table II-18. R/V&D Flight Computer Support Words

	Manual	Autonomous	Hybrid
Rendezvous	1500	1500	1500
Inspection Orbit	--	50	50
Range Control	200	200	200
LOS Control	100	100	100
Target Attitude Computation	--	750	750
Docking Port Coalign	--	200	200
Translation Loop Control	--	300	300
Docking Port Recognition	--	250	--
Abort Recognition	--	400	--
Abort Command	--	200	--
Sequencing & Control	50	250	200
Closure Initiation	50	50	50
Total	1900	4250	3350

support words that has been made for three of the selected candidate systems. While alternate segmentation of software blocks can be made, and other functions included, these estimates are believed fairly representative of manual, autonomous and hybrid system mechanizations.

D. SIMULATION SYNOPISIS

Digital simulations were used to support analyses of three principal phases of the rendezvous and docking sequence. The rendezvous phase was simulated using an existing proportional navigation program that was developed in support of Martin Marietta's planetary programs. Docking closure was simulated using a new, planar simulation developed under this contract. The dynamics of impact docking was simulated with two digital simulation programs. The first was a new simulation developed in support of this contract (under IRAD funds) that was designed to quickly identify major parametric relationships. The second was an existing program, developed under previous MSFC contracts, which

was modified to include propellant slosh modes and a new docking mechanism. This subsection summarizes the major results obtained using these simulations.

1. Rendezvous Simulation - PROGRAM RENDZ is a simulation, in three-dimensional space, of the closure of two vehicles in a central force field utilizing a proportional navigation scheme. This program provides a capability to mechanize the proportional navigation logic in different ways. The option used in this study was to describe the desired closure relationship as $R = K (\dot{R})^2$, and to maintain this relationship with pulses of axial thrusting when a prescribed deadband is exceeded. Simultaneously, line-of-sight rates were monitored. When these rates exceed a prescribed threshold, a lateral component of thrust is added to the axial thrust to null the sensed line-of-sight rate. Time of closure for a given set of initial conditions is controlled by setting the constant of proportionality relating R and $\dot{R}^2$. This program also provides an ability to study the effects of systematic sensor errors on the closure maneuver. This capability was modified during the course of the study to permit the following error types: Range and range rate measurements - a percentage error plus a bias error; line-of-sight rate - a percentage error plus a bias error; line-of-sight angle - a bias error. Typical program output for a closure from a range of 25 km (12.8 n mi) is shown in Figure II-23. This particular closure used 55 pulses totaling 7.8 m/sec (22.2 ft/sec) to achieve a closer approach of 35 meters (115 ft) at a relative velocity of 0.9 m/s (3 ft/sec). Approximately 2.3 hours was required to effect the closure.

An empirical relationship between the velocity and the time required to complete a rendezvous closure was developed by fitting the results of several closure simulations at geostationary altitude. The precise nature of this relationship is determined by the area under the prescribed $R/\dot{R}$ curve, the initial closure velocity, the non-linear orbital mechanics effects, the non-linear nature of the ON/OFF control mode and the effects of sensor errors. In spite of these fairly involved relationships, an empirical fit accuracy within 0.15 m/sec (0.5 ft/sec) was achieved. The empirical velocity/time relationship is:

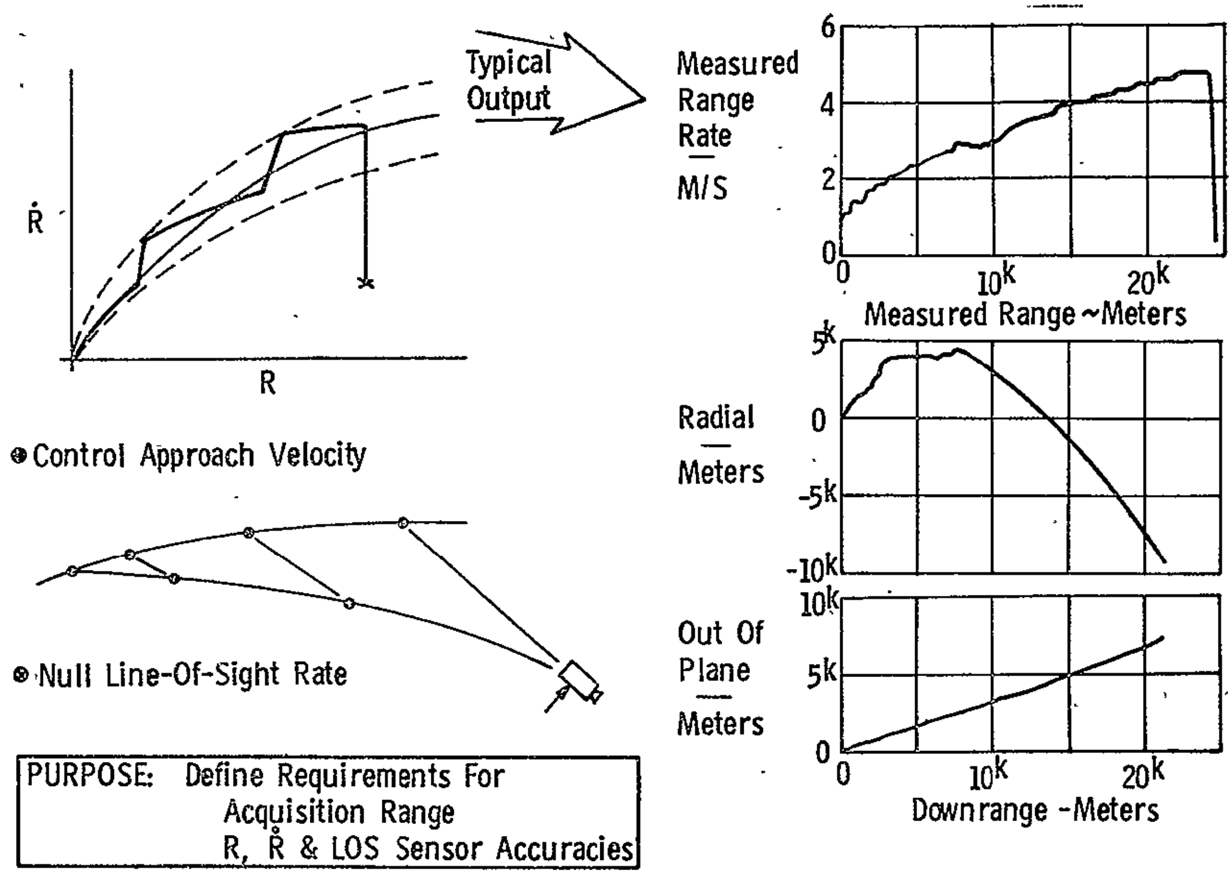


Figure II-23. PROGRAM RENDZ Summary

$$\Delta V = \left[3.0 - (2.77E\text{-}4)\frac{\Delta t^2}{\Delta R_o}\right]\left(\frac{\Delta R_o}{\Delta t}\right) + \Delta \dot{R}_o \quad \text{(English units)}$$

$$\Delta V = \left[3.0 - (.84E\text{-}4)\frac{\Delta t^2}{\Delta R_o}\right]\left(\frac{\Delta R_o}{\Delta t}\right) + \Delta \dot{R}_o \quad \text{(International units)}$$

Where;

ΔV = Maneuver Velocity Required

Δt = Time Required

ΔR_o = Relative Range at Maneuver Initiation

$\Delta \dot{R}_o$ = Relative Range Rate at Maneuver Initiation

This equation yields the velocity, range, time relationships shown in Figure II-24. Considering the acquisition range of 23 km (12.5 n mi) recommended

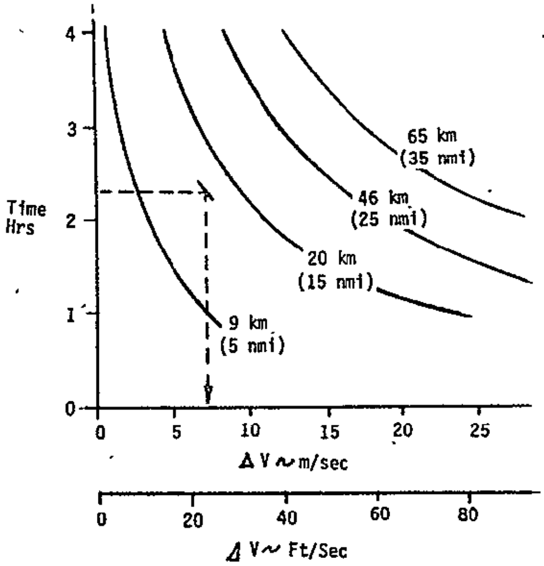


Figure II-24. Rendezvous Time Relationship

for Tug geostationary rendezvous, Tug RCS propellant budgets, and Tug timelines, rendezvous energy in the vicinity of 7 m/sec (23 ft/sec) and rendezvous time of 2.3 hours represent reasonable planning parameters.

	Typical Tolerance		Maximum Investigated
	R/F	SLR	
Range	0.5%	.01% +.3 Ft	10%
Range Rate	0.1 F/S	.02 F/S	10%
LOS	0.5°	$.01^{\circ}$	5°
LOS Rate	0.1°/Hr*	0.1°/Hr*	10.0°/Hr

Table II-19. Rendezvous Sensor Errors Investigated

The effect of sensor errors on rendezvous performance parameters when using the proportional navigation algorithm was investigated. The pertinent performance parameters are the energy required to perform the rendezvous closure, and the closest approach range to the target spacecraft. Table II-19 shows the range of sensor errors investigated. Typical errors for the SLR and RF-RADAR classes of rendezvous sensors are shown. The SLR devices are much superior to the RF sensors. Errors in order of magnitude larger than either class were investigated in the search for significant results. Neither miss distance nor energy requirements were effected in any systematic way. No velocity requirement change greater than 10% was observed. The range of closest approach varied

considerably from 100 to 500 feet, but not in a way relateable to sensor errors. It is believed that the ON/OFF nature of the navigation algorithm is a larger contributor to these parameters than sensor errors. A systematic increase in the velocity at closest approach was observed. The 10% class of errors produced a velocity in the neighborhood of 3 m/sec (10 ft/sec), as compared with a typical 1 m/sec (3 ft/sec) with no sensor errors present.

The major conclusions reached from the rendezvous phase analyses are as follows:

- The proportional navigation algorithm is suitable for directing rendezvous approach.
- This algorithm is insensitive to sensor errors, and rendezvous approach produces no driving sensor accuracy requirements.
- Geostationary rendezvous can be effectively performed in 2-2.5 hours with an energy expenditure of less than 7.6 m/sec (25 ft/sec)
- The lack of terminal precision of the rendezvous algorithm used here suggests that transfer to the inspection algorithm should be made at a relative range of at least 180 meters (600 ft).

These analyses have verified the suitability of proposed rendezvous system candidates to successfully complete the rendezvous approach phase of flight.

2. <u>Docking Simulation</u> - No digital simulation capability for the docking phase existed at the beginning of this study. Initial plans for relating sensor accuracies and operating ranges to docking mechanism requirements called for generating sensitivity relationships and generating appropriate parametric data. This was done and is reported in Section II-B of this volume. It was felt, both by the NASA COR and the study personnel, that this key phase should be verified more rigorously by simulation. Analyses of the same problem made in different ways would add to the confidence in the results. Also, the simulation generated would be a prototype of an analysis tool required later in the rendezvous and docking development program. A decision was made in late September to develop such a digital simulation program.

The primary capability required of the program was that it be capable of simulating all aspects of docking trajectory control that contribute to dispersions at the instant of contact between the Tug and target spacecraft docking mechanisms. At the same time, the program should run rapidly enough to permit Monte Carlo simulation of the varied, non-linear contributions to these dispersions.

The contributors to contact dispersion that required simulation included the following:

- o Attitude and translation control implemented by pulsing RCS nozzles in accordance with a phase-plane logic.
- o Rigid Body Dynamics.
- o Sensor errors in the measurement of relative position and attitude, and the derivation of rate information from these measurements.
- o The loss of certain measurements as the docking vehicles approach too closely for the sensors to function.
- o The performance characteristics of simplified maneuver control algorithms.
- o The effect of offset centers of gravity, probe rotation arm, translation/attitude loop cross-coupling and differential gravity effects.

The general nature of a simulation capable of addressing these requirements is illustrated in Figure II-25. The program is a planar simulation. It uses the baseline Tug attitude phase-plane logic and the indicated translation control logic to make ON/OFF decisions for each of the 24 RCS nozzles used. The steering logic incorporated in the program is very simple, but has proven effective. This version of the program simulates impact docking approach. Generation of such a simulation is not unusual, but the desire to make the program run rapidly made the problem somewhat unique. Most existing phase-plane simulations readily available run in the ne ghborhood of real-time. This would be much to slow for economical Monte Carlo simulation.

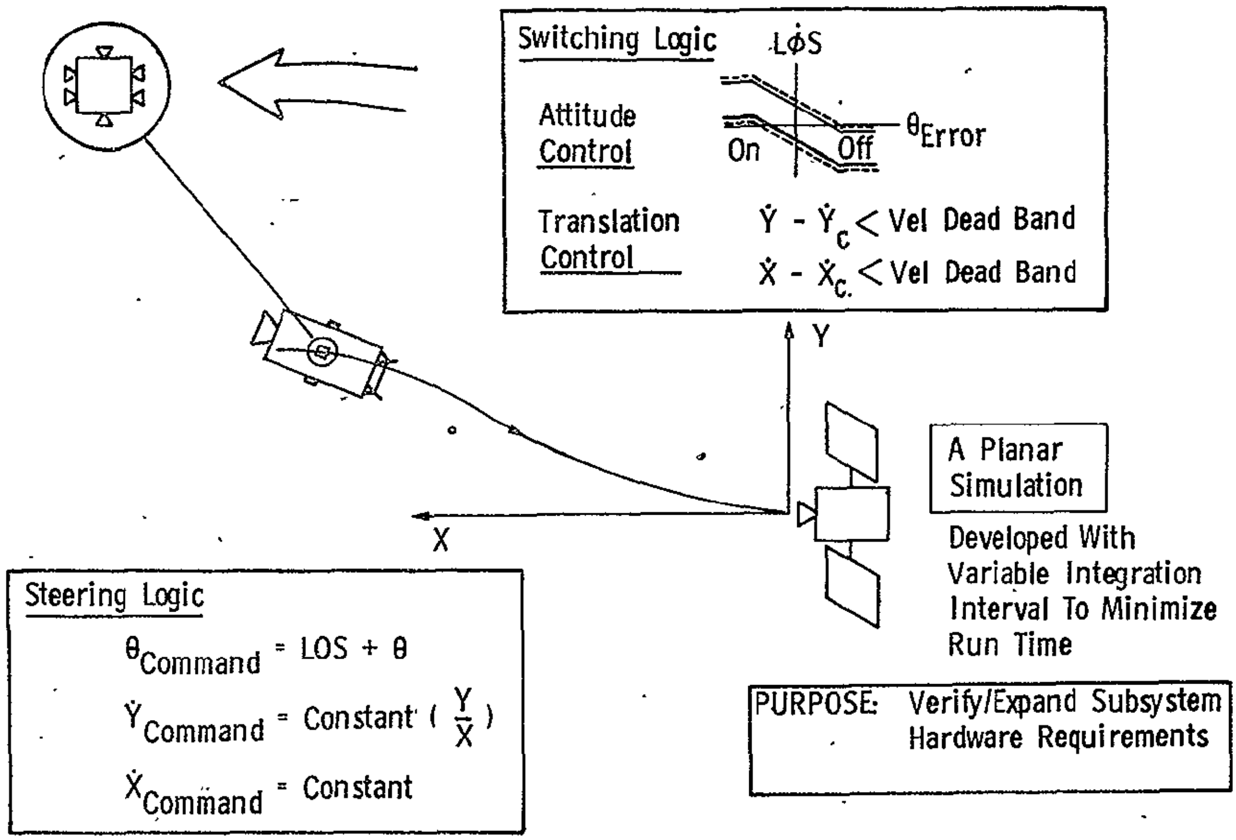


Figure II-25. PROGRAM DOCK - General Characteristics

Two steps were taken to cope with this fast run time requirement. First, the simulation was limited to a planar representation. This permits an accurate evaluation of the parameters of interest at a basic savings in computations required. Cross-coupling between axes is not represented, but this is acceptable for an initial analysis. Second, an elaborate control of computation cycles was developed. The flight computer used to implement the docking maneuver will operate on two computational intervals. The minor cycle, using an interval of about 0.020 seconds, will handle the attitude control phase-plane logic. The major cycle of about 1.00 seconds will handle navigation calculations and direct the translation control loop. In this simulation, these two computational internals and a third longer interval (a simulation speeding 'coast' interval) are implemented. Program logic uses the longest of these intervals whenever

possible, and drops back to the shorter computational interval only when it establishes that changes are occurring at the lower level. Figure II-26 illustrates, in a simplified manner, how the computational cycle control is

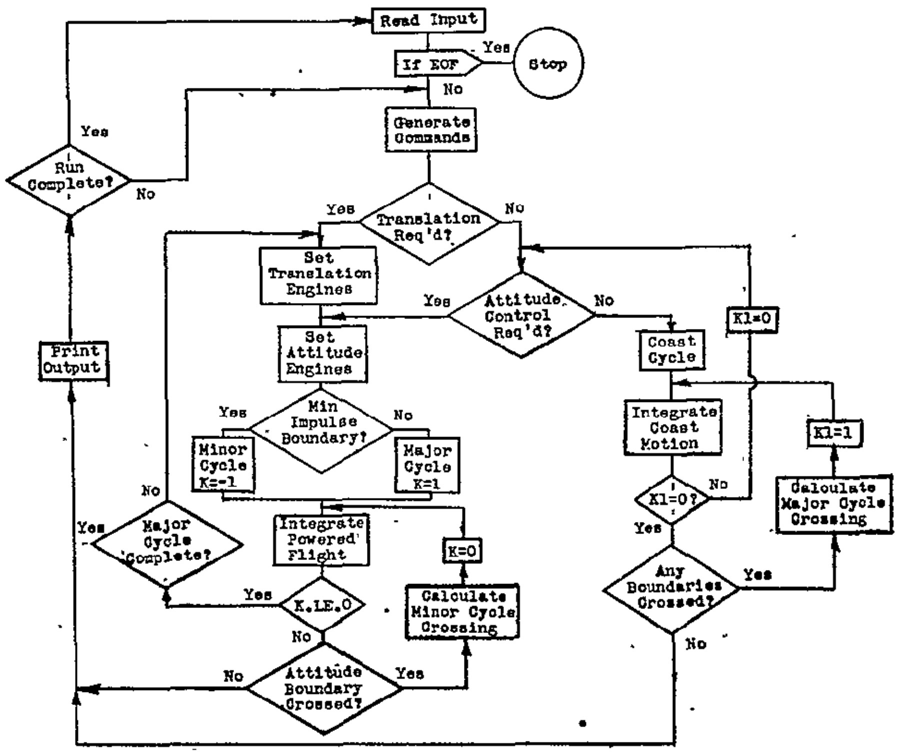


Figure II-26. Simplified PROGRAM DOCK Flow

effected in the simulation developed. The basic approach was to assume the longest interval possible, to calculate the resulting motion, to check at the end of the interval to see if any control boundaries had been crossed. In the event of a crossing, the interval was shortened as required to make the calculations valid. This procedure is more complex to code than the flight logic will be, but it has shown a great increase in computational speed. Under some circumstances, it has yielded a computational speed of 1/600 real-time.

Figure II-27 illustrates typical docking trajectory motion for the Tug center of gravity relative to the spacecraft docking axis. This run was initiated from a distance from the docking port of 61 m (200 ft) with a lateral

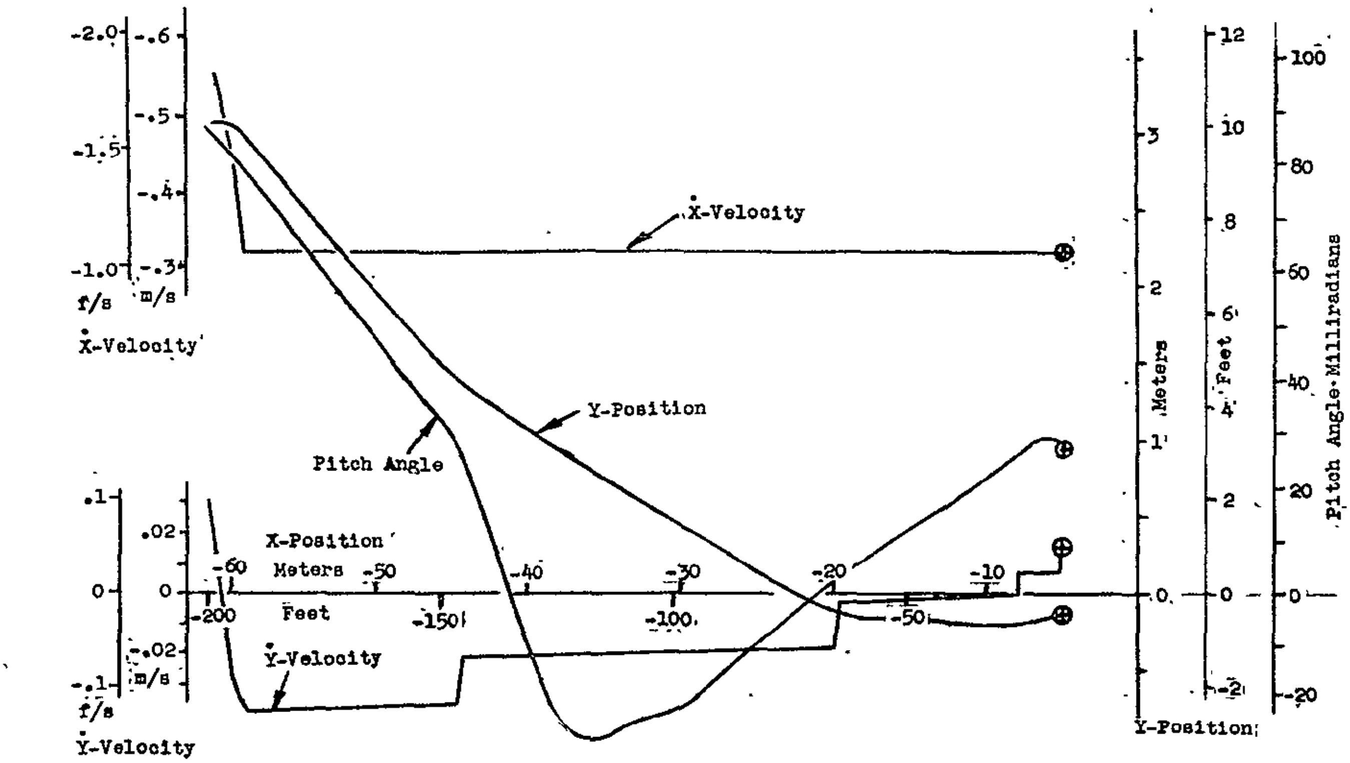


Figure II-27. C.G. Motion for Typical Docking Maneuver

offset of 3 m (10 ft) and an initial pitch angle of .087 radian (5°) with respect to the docking axis. It was commanded to approach the target spacecraft at velocity of 0.3 m/sec (1.0 ft/sec). This command was quickly achieved, within deadband tolerance, and maintained without further correction. The lateral velocity command, required to acquire the spacecraft docking axis, results in stepwise corrections to lateral velocity in accordance with the deadband characteristics. Corrections come with increasing frequency as the target is approached. Perfect lateral positioning of the Tug C.G. is not achieved with the selected deadbands. The attitude control loop, however, maintains vehicle LOS oriented at the docking port, resulting in a superior positioning of the docking probe. The motion of the centerline of the Tug docking mechanism is illustrated in Figure II-28. The lateral positioning of the probe head is considerably superior to the positioning of the center of gravity. The stepwise control of pitch rate,

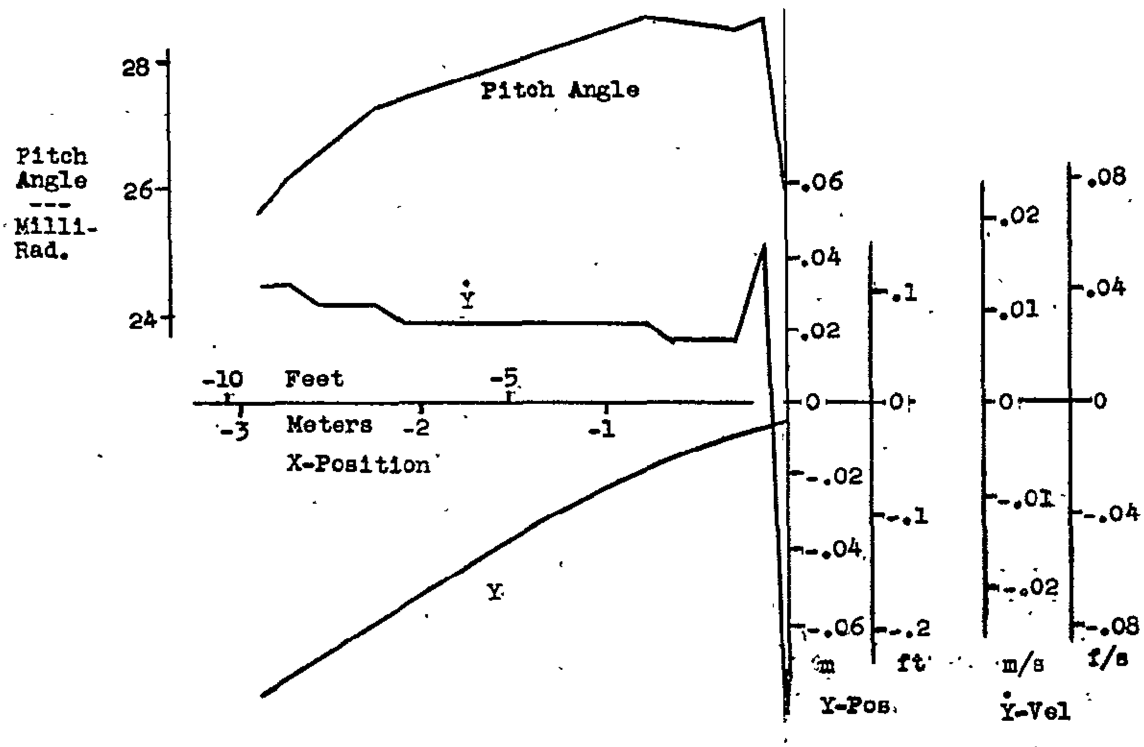


Figure II-28. Probe Motion Near Contact

and resulting stepwise variation in the lateral component of probe head velocity appears in the figure. On first observation, this performance appears generally satisfactory.

In addition to input of a physical Tug description, PROGRAM DOCK is capable of varying a range of initial conditions and sensor parameters to establish resulting impact conditions. Variable initial conditions include all planar state variables. Sensor parameters include:

RGER - Range measurement error (ft)

TAERD - Target attitude error (deg)

LOSERD - Line-of-sight error (deg)

MRRNG - Minimum range for range measurement (ft)

MRTA - Minimum range for target attitude measurement (ft)

MRLOS - Minimum range for line-of-sight measurement (ft)

VHER - Accuracy with which horizontal velocity can be derived (ft/sec)

VVER - Accuracy with which lateral velocity can be derived (ft/sec)

A series of runs was made varying these parameters one at a time to establish their individual effects. The results were somewhat inconclusive, since the effects were masked by the deadband effects of the Tug control systems. About all that could be discerned was that the system could cope, with varying degrees of success, with all the variables. One not surprising result was that the ability to derive lateral velocity became quite important when it was coupled with a loss of measurement at a large distance from the target spacecraft.

In any event, it was decided that this simulation should be run in a Monte Carlo mode, where random selections of input variables were run individually, and the net result observed to determine statistical effects. Accordingly, the following variables were selected for random variation:

- o Five sensor errors (RGER, TAERD, LOSERD, VVER, VHER)
- o Five initial conditions ($\dot{X}$, Y, $\dot{Y}$, θ, $\dot{\theta}$)

An input of a 3-sigma variation in these parameters is accepted in a modified version of the program. A prescribable number of runs can be made where each run is made with a value for each of the ten variables randomly selected from a normal distribution.

This version of PROGRAM DOCK was used to translate the typical docking parameter variations shown in Table II-20 into the impact dispersions shown in Figure II-29. The parameter variations are considered representative of an autonomous docking system. The impact dispersion shown are for 100 runs randomly selected from the parameter variations. This number of runs is insufficient to develop a good statistical sample, but the ellipses shown on Figure II.D.2-7 are believed representative of 2-sigma variations in impact dispersion. In Section II.B of this volume, these results are compared with the linear sensitivity analyses developed earlier. The agreement is generally satisfactory. The primary specifications developed in Section II.B were that the docking mechanism should be able to deal with an angular misalignment of 0.08 rad (4.5°),

Table II-20. Docking Parameter Variations

	3σ Initial Condition Dispersions	3σ Measurement Errors
X_o = 200' (61m)	$\Delta \dot{X}_o$ = .6 m/s (2 ft)	ΔLOS = .009 rad (0.5 deg)
Minimum Measurement Ranges	ΔY_o = 6 m (20 ft)	ΔT.A. = .017 rad (1.0 deg)
	$\Delta \dot{Y}_o$ = .6 m/s (2 ft/sec)	ΔRange = .15 m (0.5 ft)
LOS - .3 m (1 ft)	$\Delta \theta_o$ = .03 rad (1.5 deg)	ΔHorizontal Velocity = .003 m/s (0.01 ft/sec)
Range -.. 3 m (10 ft)	$\Delta \dot{\theta}_o$ = .06 m/s (0.2 deg/sec)	ΔVertical Velocity = .008 m/s (0.025 ft/sec)

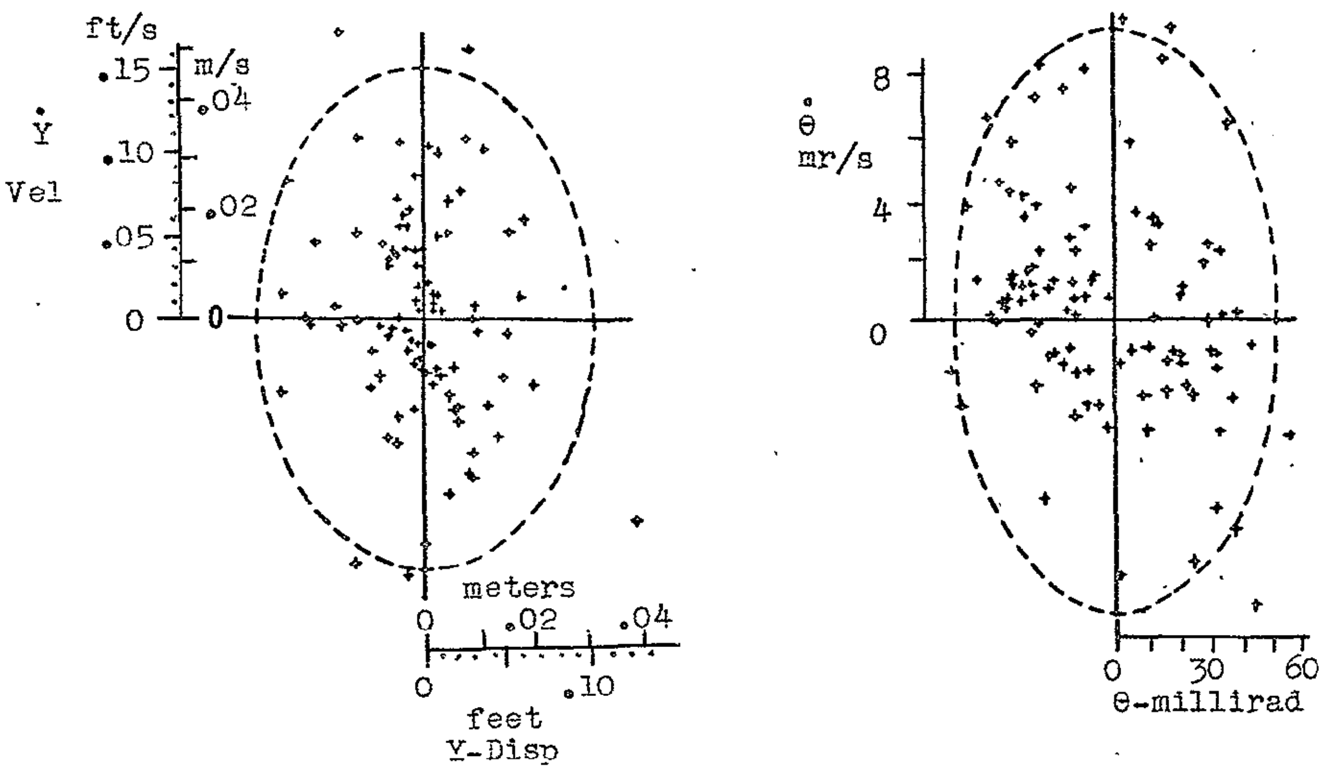


Figure II-29. Docking Impact Dispersions

a lateral misalignment of 0.1 m (.32 ft), and a lateral tip velocity of .03 m/s (.1 fps). The first two of these specifications agree well with the sim lation results. The last is somewhat exceeded by the simulation results. Some further evaluation should be conducted to establish the criticality of this parameter, and means of reducing it (perhaps by adjusting the closure algorithm) if it proves advisable.

The next step in docking closure simulation should include three advances to the version of PROGRAM DOCK developed under this contract. A stationkeeping phase-plane control mode should be developed. This control mode would be analogous to the attitude phase-plane control already incorporated. The axes on the phase-plane plot would be relative position and relative velocity. This control should be capable of hovering within mechanical grasping range--in the neighborhood of .6 to .9 meters (2 to 3 feet). Relative sensed data, of course, would be required at these ranges to effect such control. The second expansion to the simulation should be the incorporation of an ability to represent motions in 3-dimensional space. The control modes in pitch/vertical translation and yaw/lateral translation would be mechanized independently. The simulation would assure that there are no serious cross-coupling effects. The final addition required in the simulation is inclusion of the effects of RCS plume impingement on the relative motion between the docking vehicles. These forces could require revision of the control logic to effect a successful docking. Further, the nature of the impingement could have undesirable effects on spacecraft sensors, such effects need quantization and coordination with potential spacecraft users.

3. Docking Dynamics - Docking dynamic analyses of the Tug to various spacecraft are necessary and required to assess the overall impact maneuver as related to impact attenuation mechanism design for both Tug and spacecraft, possible requirements for limiting large amplitude fluid motions, and pre- and post-latch control system requirements. This section details the two-phase approach to docking dynamics analysis that was developed, validated and implemented during the course of these studies and summarizes the numerical investigations. A complete description of the analyses and supporting digital computer programs appears in Volume IV - Supporting Analyses.

During the early stages of the study, it was established that the originally proposed plan to use the Martin Marietta developed digital code for detailed docking analyses (IMPRES) would not provide a cost effective approach due to the long computer running times associated with this digital code combined with the fact that the impact attenuation mechanism, Tug flexible body properties and control system logic were not sufficiently defined to warrant such a detailed investigation. It was therefore decided to implement a two-phase approach to problem solution where Phase I would provide a new analytical tool to be used to examine the total dynamical system in the large and Phase II would use a modification of the IMPRES code for a selected few impact analyses. Both analytical tools incorporate an analog to simulate large amplitude fluid excursions and provide an assessment of vehicle and fluid motions as well as definition of interface forces realized during a docking maneuver.

The Phase I approach is structured such that the total dynamical system (including Tug structure, propulsion tanks, spacecraft and attenuation mechanisms) is considered to be an assembly of interconnected substructures. The entire system (or portions thereof) may be spinning or nonspinning and individual bodies of the system are capable of undergoing large relative excursions with respect to each other. The system is, by its nature, a feedback system wherein inertial forces (e.g., centrifugal and Coriolis accelerations) and restoring and damping forces are motion

dependent. A control system may be included to actively control position and rate error through use of reaction control jets, servomotors, or momentum wheels. The bodies of the system are interconnected via linear or nonlinear springs and dashpots, by gimbal/slider block combinations, or a combination of the above. Any two bodies may be free (one from the other) with six degrees of relative motion freedom and, additionally, any or all of the six degrees of freedom between two bodies may be controlled as an explicitly prescribed function of time.

With reference to Figure II-30, the mechanical system consists of six bodies which are connected to form a composite two-body system where the composite Tug vehicle consists of the Tug structure,

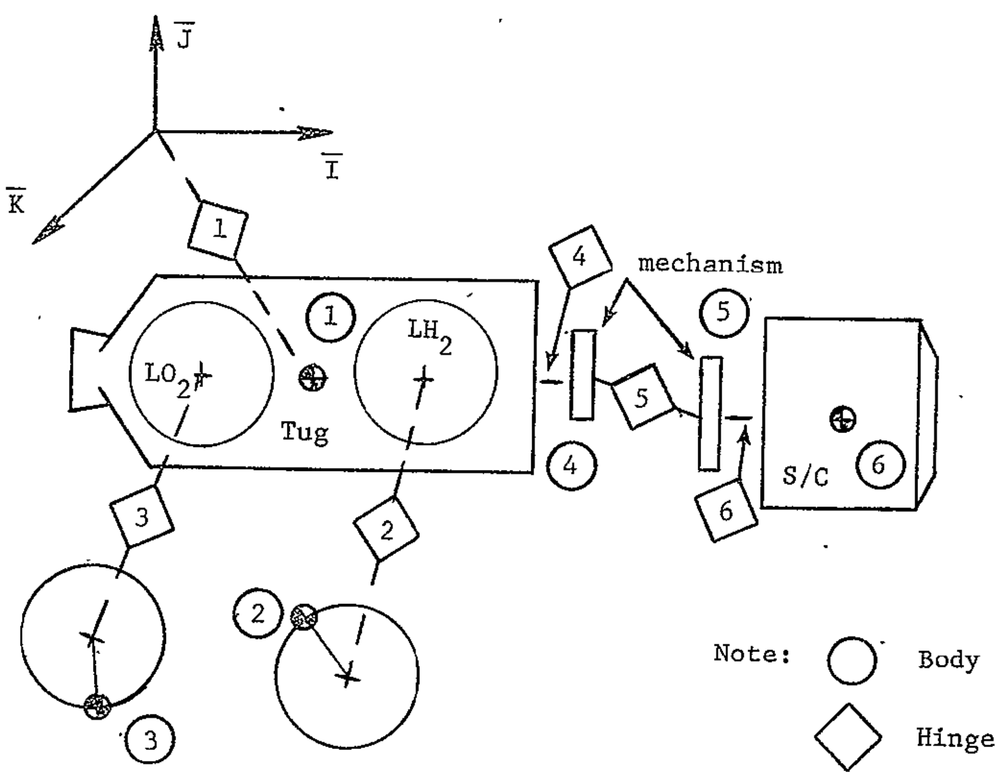


Figure II-30 Tug/Spacecraft System, Phase I Study

attenuation mechanism and two fluid pendulum masses and the composite spacecraft consists of the vehicle and its associated attenuation mechanism. The attenuation mechanisms may have one or more relative degrees of freedom with respect to their associated vehicles to simulate the stiffness and damping effects of attachment structure; the fluid mass pendulums have three relative degrees of freedom with respect to the Tug structure.

A fixed length pendulum analog simulates the mass associated with the liquid hydrogen and liquid oxygen propellants. This is equivalent to specifying that the propellants are constrained to move as a point mass on a spherical surface; the radius of the sphere being adjustable with various tank fill levels (the lower the fill level, the larger the equivalent radius). This assumption of a spherical constraint surface is not unduly restrictive in view of the known Tug tank geometry.

The Phase II approach was centered about the Martin Marietta developed IMPRES code* as modified to consider the effects of large amplitude fluid motions. In this formalism the Tug (chase vehicle), spacecraft (target vehicle), and their associated docking/attenuation mechanisms are considered as separate entities. Either vehicle may be characterized as a rigid or flexible body and may be spinning or nonspinning. A significand feature is the definition of the attenuation mechanisms which are modeled as an assembly of interconnected rigid links (elements) which are in turn connected by linear or nonlinear springs and/or dashpots and which may experience large relative excursions with respect to each other. The total mechanism is then assembled from a library of geometric shapes including rods, tubes, cones, spheres, helixes, etc. In this manner the analyst may describe a physical system in great detail as shown schematically in Figure II-31 where a typical probe/drogue attenuation mechanism is indicated. The system governing equations of motion follow from Hamilton's equations with constraints. This technique permits an exact

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* Orbital Docking Dynamics, MCR-74-23, Martin Marietta Corporation, April 1974

numerical simulation of the impact maneuver in that unilateral constraint conditions are implemented and the actual process of initial mechanism contact, sliding, possible rebound and recontact, and ultimate capture is represented.

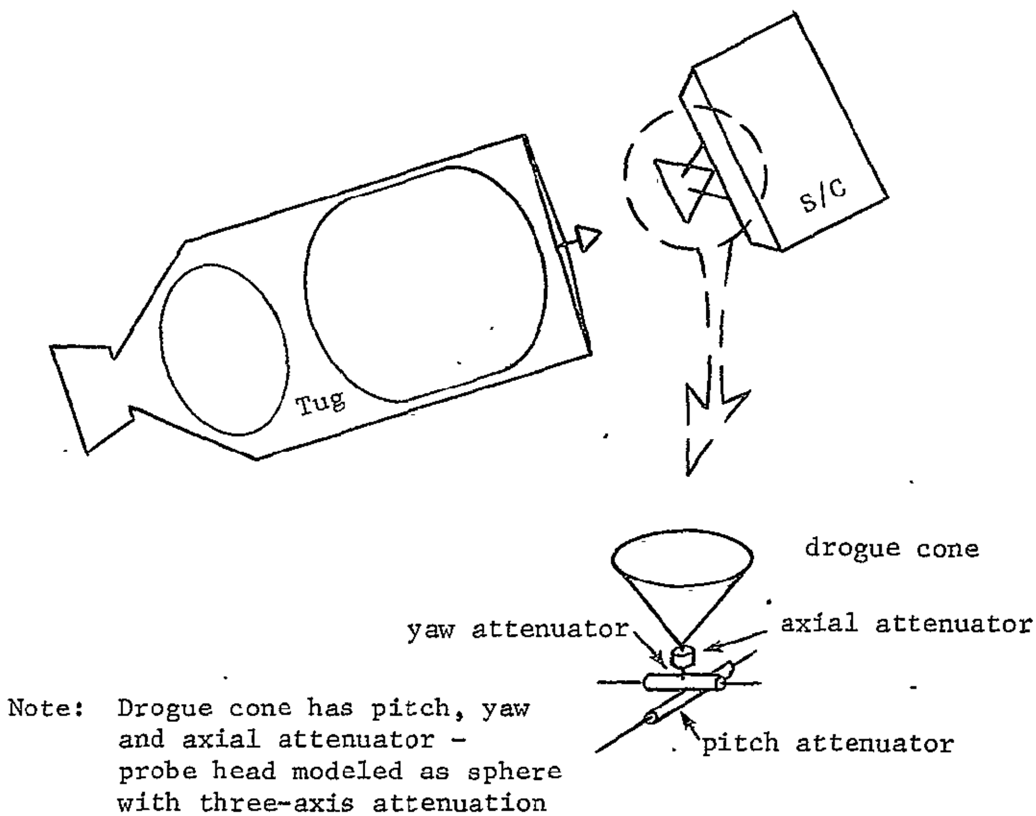

Figure II-31 Tug/Spacecraft System, Phase II Study

During these investigations, the IMPRES program was modified to accept a large amplitude fluid motion analog that is considerably more general than the analog developed under Phase I. Here the fluid is again assumed to move as a point mass on a constraint surface but the surface is assumed ellipsoidal. This analog was originally developed by Martin

Marietta Corporation and has been shown to yield excellent correlation with experimental data*. A modification to the basic equations of motion was necessary to implement the analog; the technique is summarized in Volume IV - Supporting Analyses.

The intent of the numerical studies was to establish those system parameters which most influence the docking maneuver and to isolate potential problem areas that might require further or extended investigation. Several system characterizing parameters were selected for investigation studies performed to establish gross effects and relative sensitivity of the response to variations in the parameters.

The possibility of large amplitude fluid excursions and the resulting effect upon the maneuver was defined to be of major interest as were the effects of variations in Tug tank fill level and variations in time to execute the maneuver. Variations in attachment structure stiffness and damping characteristics were felt to be of lesser importance as were variations in spacecraft inertial characteristics and the initial position of propellants within the tanks.

Several important and interesting conclusions were established as a result of the numerical studies. Some of these conclusions are significant with respect to the impact docking maneuver itself; others are significant with respect to post-latch system requirements.

The effects of propellant motions, in that the propellant masses combine to represent (for nominal burn conditions) a large fraction of the total system mass, are appreciable when the entire maneuver including post-latch vehicle motions is considered. For nominal time to execute the impact, closure and latch condition, the resulting propellant excursions are seen to be relatively small as would be expected. These excursions are on the order of a few degrees and do not significantly affect the total system dynamic response or resultant interface load requirements.

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* Experimental Study of Transient Liquid Motion in Orbiting Spacecraft, MCR-75-4, Martin Marietta Corporation, February 1975.

On the other hand, nominal acceleration profiles resulting from nominal initial offsets and rates, are shown to yield relatively large residual propellant rates which may have (over long periods of time) a significant effect upon post-latch system motions and may well impact Tug control system requirements. This would indicate that some form of propellant management device (perhaps tank baffles) may be required. Further studies in this area appear warranted.

Of major concern to the attenuation mechanism designer is the accommodation of interface loads; a measure of which was established through examination of representative Tug/spacecraft impact maneuvers. An Apollo/Skylab-type probe/drogue mechanism and representative initial conditions and Tug propellant fill conditions were employed in several simulations. The results indicate that the docking interface forces and torques are relatively insensitive to spacecraft inertial characteristics and Tug fill level but are quite sensitive to the relative vehicle rates at impact, increasing markedly with increasing impact velocity. However, the resultant interface load levels are, in general, rather moderate and probably will not be critical to mechanism design. Should this not prove to be the case, some means of Tug translational control during the capture phase (with resultant increase in time from initial impact to final latch) may be used to alleviate undesirable loading conditions. It must be pointed out here that these studies considered no flexible body properties of either vehicle and therefore there is no measure available of the dynamic response of spacecraft solar panels or other flexible appendages. If, for given class of spacecraft, it becomes necessary to maintain structural integrity during the docking maneuver, the analyses should be extended to consider vehicle flexibility and the possible requirement for stowage of the flexible appendages.

III. SYSTEM SELECTION

This section will result in recommended configurations for a manual, an autonomous and a hybrid rendezvous and docking system for the Space Tug. Each configuration will be discussed individually. For each, the following data will be presented: (1) a strategy, or sequence of events, (2) a brief description of the candidates that were configured for evaluation, (3) criteria used for the evaluation process, (4) the method by which the candidates were ranked, (5) the results of the ranking in the form of the best three candidates and rationale for their selection, and finally (6) a more detailed description of the best candidate, including cost estimates.

A. MANUAL CONFIGURATION

The strategy adopted for the non-impact manual configuration, in the form of a sequence of events, is as follows:

1) Sequence starts with ranging sensor acquisition at 23 Km (12.5 n mi).
2) Ranging sensor data is used to perform terminal rendezvous to stationkeeping at inspection range of ~ 30 m (100 ft) while ground monitors the TV image. Tug attitude is controlled from sensor LOS data.
3) The ground initiates inspection (preprogrammed or manual lateral translation of known duration and direction). It is assumed the docking port attitude is known.
4) The ranging sensor corrects LOS during inspection. The ground monitors and can back it up if acquisition is lost, or whatever.
5) Manual +X thrusting is used to correct for orbit's normal acceleration.
6) The docking port is located visually.
7) The ground manually stops the inspection orbit (reverse lateral thrusting).
8) The crew manually aligns to the docking port axis by performing lateral thrusting, using an offset T as a cue, while

the ranging sensor and/or manual ground commands, maintain LOS on the target. The Tug is now in an inertial attitude hold mode unless overriden by manual or sensor generated commands.

9) If all looks well; e.g., lighting, spacecraft stability, etc., a predetermined (from Tug mass, ACS thrust, etc.) translation is manually commanded to achieve $\sim$ .3 m (1 fps) closing velocity.

10) The ranging sensor monitors and trims that velocity during the first few seconds. It could also command it, if desired, with manual command as a backup.

11) As the vehicle closes, the ground monitors range and range rate data from the ranging sensor on a TV screen. Vehicle lateral thrusting is commanded to align the offset "T" target on the spacecraft (ACS pulsing would be in a minimum impulse mode. The number desired would be determined by crew judgment based on the "T" offset and range). The Tug attitude is maintained by ranging sensor LOS data to the corner reflector until that is not accurately available. At that time GN&C inertial attitude hold is maintained. Ranging sensor range and range rate data is lost at $\sim$ .9 to 3 m (3 - 10 ft). Manual lateral translation corrections may still be sent, based on offset "T" viewing, but few are likely since less than 10 seconds remain until docking V_X = .3 m/sec (1 ft/sec) .

12) Docking occurs; spacecraft attitude control is deactivated.

13) Mechanism contact monitoring is conducted.

14) Hard latch is commanded.

The non-impact manual configuration is the same as the impact docking for the rendezvous and inspection phases; Steps 1 through 8 in the previous sequence, but from there to docking the following steps are followed:

9) If all looks well; e.g., lighting, spacecraft stability, etc., a predetermined translation is manually commanded to achieve $\sim$ .15 m/s (.5 fps) closing velocity.

10) The ranging sensor will monitor and trim this velocity during the first few seconds (it may even initiate it). Range and range rate data will be provided to the ground along with TV pictures. At predetermined range gates, the range rate will be reduced manually based on precalculated thrusting durations.
11) Range rate equals 0.0 m/s at .9 - 1.5 m (3 - 5 foot) range. The man will continue to monitor the visual display to ensure a stationkeeping mode.
12) The ranging sensor will maintain the LOS automatically, or it can be provided manually.
13) Docking axes co-alignment will be provided by lateral thrusting commands from the ground based on an offset "T" or similar TV target. Consequently, a target attitude determination capability will not be provided. Range sensor range and range rate data is highly desirable at close-in ranges to provide more continuous and real time data on the ground for monitoring to see that stationkeeping continues to be maintained within a fairly rigid band during STEM insertion.
14) On verification of stable stationkeeping, a separate ground controller will command extension of the STEM.
15) Observing the TV picture (once each 16 seconds or less), the STEM will be inserted into the drogue by commanding STEM pitch, yaw, and extend/retract commands.
16) On receipt of a STEM contact signal, the tug will maintain its attitude at the time of contact and the vehicles will slowly be drawn together by manual control of the STEM.
17) Soft contact is monitored.
18) At contact the hard dock latches are commanded closed and the target vehicle control system is disabled.

Based on these sequences, candidates were configured from the hardware components presented in Section II.C. All combinations of hardware elements that met the requirements of IIA and B were considered. The resulting list of 19 candidates is shown in Table III-1.

Table III-1. Manual Candidate Summary

Candidate	Sensor	Docking Mechanism	Weight - Kg (Lb) Mechanism	Weight - Kg (Lb) R&R Sensor	Weight - Kg (Lb) TV Lights	Power Sensor	Power TV
M1	GaAs SLR	MDAC	252 (556)	25 (55)	9 (20)	40	12
M2	TV	MMSE	440 (970)	25 (55)	9 (20)	40	12
M3		Non-Impact	241 (531)	25 (55)	9 (20)	40	12
M4	CO_2 Laser	MDAC	252 (556)	22.7 (50)	9 (20)	200	12
M5	(Non-Cooperative)	MMSE	440 (970)	11.7 (50)	9 (20)	200	12
M6	TV	Non-Impact	241 (531)	22.7 (50)	9 (20)	200	12
M7	CO_2 Laser	MDAC	252 (556)	18 (40)	9 (20)	100	12
M8	(Cooperative)	MMSE	440 (970)	18 (40)	9 (20)	100	12
M9	TV	Non-Impact	241 (531)	18 (40)	9 (20)	100	12
M10	Rend. Radar	MDAC	252 (556)	34 (75)	9 (20)	275	12
M11	(Non-Cooperative)	MMSE	440 (970)	34 (75)	9 (20)	275	12
	TV						
M12	Rend. Radar	MDAC	252 (556)	32 (70)	9 (20)	120	12
M13	(Cooperative)	MMSE	440 (970)	32 (70)	9 (20)	120	12
	TV						
M14	Dual Mode Radar	MDAC	252 (556)	36 (80)	9 (20)	275	12
M15	(Non-Cooperative)	MMSE	440 (970)	36 (80)	9 (20)	275	12
M16	TV	Non-Impact	241 (531)	36 (80)	9 (20)	275	12
M17	Dual Mode Radar	MDAC	252 (556)	34 (75)	9 (20)	120	12
M18	(Cooperative)	MMSE	440 (970)	34 (75)	9 (20)	120	12
M19	TV	Non-Impact	241 (531)	34 (75)	9 (20)	120	12

Approximate weights and power consumption data is shown for each.

There are really just seven distinct sensor groups and three of those are merely cooperative versions of a non-cooperative sensor. The 19 candidates arise from combining each of the sensor groups with the three different docking mechanism . The RF rendezvous radar is combined with impact mechanisms only (MDAC square frame and MMSE) since the rendezvous radar alone cannot accomplish a non-impact stationkeeping within the established requirements.

The method of evaluating these candidates is illustrated in Table III-2. A set of evaluation criteria was selected, shown at the left of the table.

Weighting factors were assigned to each criteria as shown in the "Weight" column. A 1 is less important, while a 3 is of higher importance. Rationale for each of the weighting factors is provided below.

1. Manual Candidate Evaluation - The evaluation matrix for the manned candidates is shown in Table III-2 for each of the 19 manual candidates in Table III-1. The first column for each candidate is a rating (R) for that candidate, while the second is a value (V) obtained from the rating multiplied by the weighting factor. The rationale for the weighting factors is provided in (a) below and rationale for the ratings in (b). The criteria can generally be grouped in three categories: (1) those that are Tug design related, (2) those that are S/C related and, finally, (3) mission and operations oriented criteria. In assigning weighting factors to the criteria, it has been assumed that the rendezvous and docking system is really provided as a service to the S/C community, therefore, those factors that enhance attractiveness to the spacecraft, Group 2, are weighted highest.

a. Weighting Rationale -

Mechanism Weight - Mechanism weights are large and vary widely so they are important, but they impact the Tug design only, not S/C or mission. Consequently, a weighting of 2 is assigned.

Sensor Weights - The deviations in weight from sensor to sensor are less than half those of the mechanism; consequently, a weight of 1 was assigned.

Power - Only the sensors really require any power. There are some reasonably large differences from sensor to sensor, but none appear to be beyond accommodation in a Tug power subsystem design, therefore, a 1 was assigned.

Development Risk - Some candidate systems contain features or hardware that present greater risks in developing successfully. These reflect in higher costs but, in addition, raise concerns among the program management and potential users as to flight worthiness at the promised flight date. This is a far-reaching concern, but the anticipated lead times before the first flight for the Tug should allow considerable reduction of most risks; consequently, a 2 was assigned.

Table III-2 Manual Candidate Evaluation

Evaluation Criteria	Weight	CANDIDATE																																					
		M1		M2		M3		M4		M5		M6		M7		M8		M9		M10		M11		M12		M13		M14		M15		M16		M17		M18		M19	
		R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V
Mechanism Weight	2	4	8	1	2	4	8	4	8	1	2	4	8	4	8	1	2	4	8	4	8	4	8	4	8	4	8	4	8	1	2	4	8	4	8	1	2	4	8
Sensor Weight	1	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	2	2	2	2	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	3
Power	1	5	5	5	5	5	5	1	1	1	1	1	1	3	3	3	3	3	3	2	2	2	2	4	4	4	4	2	2	2	2	2	2	4	4	4	4	4	4
Development Risk	2	3	6	3	6	3	6	1	2	1	2	1	2	2	4	2	4	2	4	5	10	5	10	5	10	4	8	4	8	4	8	4	8	4	8	4	8	4	8
Mission Success Probability	2	4	8	4	8	5	10	5	10	5	10	5	10	5	10	5	10	5	10	3	6	3	6	3	6	3	6	5	10	5	10	5	10	5	10	5	10	5	10
Software	2	4	8	4	8	3	6	4	8	4	8	3	6	4	8	4	8	3	6	4	8	4	8	4	8	4	8	4	8	4	8	3	6	4	8	4	8	3	6
Mission Operations (Complex.)	2	3	6	3	6	2	4	3	6	3	6	2	4	3	6	3	6	2	4	4	8	4	8	4	8	4	8	3	6	3	6	2	4	3	6	3	6	2	4
Servicing Potential	3	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	3	9	3	9	3	9	2	6	5	15	3	9	2	6	5	15
Spinning Spacecraft Compat.	2	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	4	8	4	8	4	8	4	8	2	4	4	8	4	8	2	4
Spacecraft Impact-Struct.	3	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	3	9	3	9	3	9	3	9	4	12	3	9	3	9	4	12
Spacecraft Impact-Cues	2	4	8	4	8	4	8	5	10	5	10	5	10	4	8	4	8	4	8	5	10	5	10	1	2	1	2	4	8	4	8	4	8	1	2	1	2	1	2
Ground Operations (GSE)	1	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	2	2	3	3	2	2	3	3	3	3	2	2	3	3
Recurring Cost	2	3	6	2	4	3	6	2	4	1	2	2	4	2	4	1	2	2	4	5	10	4	8	5	10	4	8	4	8	3	6	4	8	4	8	3	6	4	8
Nonrecurring Cost	2	3	6	4	8	2	4	1	2	1	2	1	2	1	5	1	2	1	2	5	10	5	10	5	10	5	10	4	8	5	10	3	6	4	8	5	10	3	6
TOTAL		95		84		95		84		72		87		87		75		88		103		97		98		95		97		87		96		94		84		92	
Docking Mechanism		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		MDAC		MMSE		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact	
Sensor Group		SLR (Coop.) TV						CO_2 Laser (Noncoop.) TV						CO_2 Laser (Coop.) TV						Rend. RF Radar (Noncoop.) TV				Rend. RF Radar (Coop.) TV				Dual Mode RF Radar (Noncoop) TV						Dual Mode RF Radar (Coop.) TV					

NOTES:

Weight: 1 = less important; 3 = more important

R = Rating, 1 = poor; 5 = good

V = Value which is weight x rating

Mission Success Probability - This criteria really relates to the complexity and flight experience of a candidate and its potential for presenting problems during operation that can impact a mission's success. It is of concern to Tug designers, as well as the payload community. Again, the development time available should allow for minimizing many of these operational concerns; hence, a 2 is assigned.

Software - Large software requirements present their own set of risks, concerns, and costs, as well as a potentially troublesome interface with the Tug computer software world. These are desirable to be avoided, yet are of no concern to the spacecraft suppliers; consequently, no more than a 2 is justified.

Mission Operations - In this evaluation this relates primarily to the complexity of the ground operations required to support the vehicle during rendezvous and docking; i.e., are 2 or 5 men required? how much data must be processed?, etc. This is important, especially considering the many recurring missions. It does not warrant more than a 2, however, since the relative costs are not really all that great for ground operations as opposed to flight.

Servicing Potential - This is a principal spacecraft concern. Its presence can greatly influence the spacecraft supplier to use the Tug's services; consequently, this is weighted a 3.

Spinning Spacecraft Compatibility - This also is an item of concern to the spacecraft supplier, however, few spinning spacecraft are currently considered potential users of the Tug retrieval capability. A weighting of 1 was assigned.

S/C Impact (Structure) - To the payload supplier the impact on his structure design to provide for docking is a major concern; consequently, it is weighted a 3.

S/C Impact (Cues) - This is similar to the above paragraph, but the magnitude of the impact is only pounds vs 10's of lbs, so it is rated a 2.

Ground Operations (ESE) - Some candidates will require more extensive checkout or may provide some inaccessibility to payloads, particularly when more

than one is to be delivered, but, in general, these are relatively minor concerns and all can be solved with proper design. A weighting of 1 is assigned.

Recurring Cost - Non-Recurring Cost - In GDC's avionics study these costs both fell in the $10 to $20 million range; consequently, should be weighted equally unless there are programmatic reasons why funding for one or the other will be particularly difficult to obtain in a given time frame. The downstream scheduling of Tug does not currently provide any insight into such problems. A 2 was assigned to both criteria.

b. Rating Rationale - Some general features and characteristics were evident that influenced the ratings in Table III-2. They are summarized below.

Docking Mechanism - The MDAC square frame is a medium weight, relatively complex scheme that is not currently developed. It is basically an impact system, not ideal for servicing, but a capability for docking with spinning satellites is feasible.

The MMSE is a very heavy scheme, but does use some developed hardware; the Apollo probe and drogue. It is less suited to servicing than the MDAC.

The non-impact device with a STEM probe is a medium weight. It is ideally suited to servicing, though not to spinning spacecraft retrieval. It is a paper design only. It has a higher risk regarding mission success and a greater mission operations complexity for the manual configuration because of the additional control required from the ground for STEM articulation, as well as close-in vehicle stationkeeping. The software requirements are slightly higher.

Sensors - There are seven sensor groups, each of which has a TV for the closure and docking operation. Three of the sensor groups are merely cooperative versions of the RF rendezvous radar, CO_2 laser radar and the dual mode (close-in and far-out) RF radar. The only real difference between the cooperative and non-cooperative is that the latter has the advantage of requiring no reflectors on the target for ranging. In all cases, however, the power (and consequently the weight) of the non-cooperative versions is higher. The GaAs SLR does not have the power capability for a non-cooperative mode.

The RF rendezvous radar is an Apollo program developed unit. The dual mode RF radar, however, includes a close-in capability which has not been developed. The CO_2 laser is complex and has no real development, to date. The GaAs SLR is relatively complex also, but has been under development for some time. It has not flown in space.

2. <u>Selection</u> - From the 19 candidates, the three highest ranked are shown below in Table III-3.

Table III-3. Highest Ranked Manual Candidates

Rank (Score)	Sensors	Mechanism
1 (103)	RF Rendezvous Radar (Non-cooperative) and TV M10	MDAC Square Frame
2 (96)	Dual Mode RF Radar (Non-cooperative) and TV M14	Non-Impact System
3 (95)	GaAs SLR and TV M1	Non-Impact System

An evaluation score generated in the manner illustrated is not sufficient justification alone for corroborate ranking. There is additional rationale that corroborates the above selection

The RF rendezvous radar/TV sensor package was ranked No. 1, primarily due to the developed state of the sensors. Costs and development risks are minimized as are cue impact on the S/C. One concern with this candidate is the heavy load on the TV and man to accomplish the final docking phases with no real backups available. There is not as much growth to greater accuracy or other performance capability, but it does meet the established requirements and for what is probably a significantly lower cost than the other candidates.

The remaining two candidates are potentially more capable, but are more costly as well. Both utilize the non-impact docking mechanism, thus providing somewhat improved accommodation for servicing, which the first one does not.

C-2

Both have the capability of providing target attitude data, if necessary. More redundancy is inherent, however, more development is required as well. The latter candidates do not require total dependence on the ground for commands, nor do they require TV algorithms to derive range data. There is more flexibility in implementing vehicle control as more reliable data is available to work with to provide some backup control in the event of ground link data loss.

3. Description - Figure III-1 pictorially shows the elements of the highest ranked manual candidates. The interface with other Tug electronics is shown as well as the software programs required in the Tug computer. A detailed description of all software routines is provided in the autonomous candidate description, Part B. Refer to the applicable software routine descriptions in that part.

The RF rendezvous radar needs no cues; it ranges on skin track data. The TV will utilize target outline and centroid data computations for LOS and range information. The only S/C cue is an offset "T" or similar cue for providing target attitude misalignment and LOS data to the ground via TV. The unique TV algorithms that compute target information from imaging data are implemented in a small 2K word microprocessor contained on one or two boards in the TV electronics. This minimizes Tug computer software and maintains a simple uniform interface between the rendezvous and docking system and the mother vehicle; be it Tug, Space Station, manned Tug, etc.

A more detailed discussion of image data processing to derive rendezvous and docking control parameters is provided under "Video Sensor Analysis" in Part B of Section VI in Volume II.

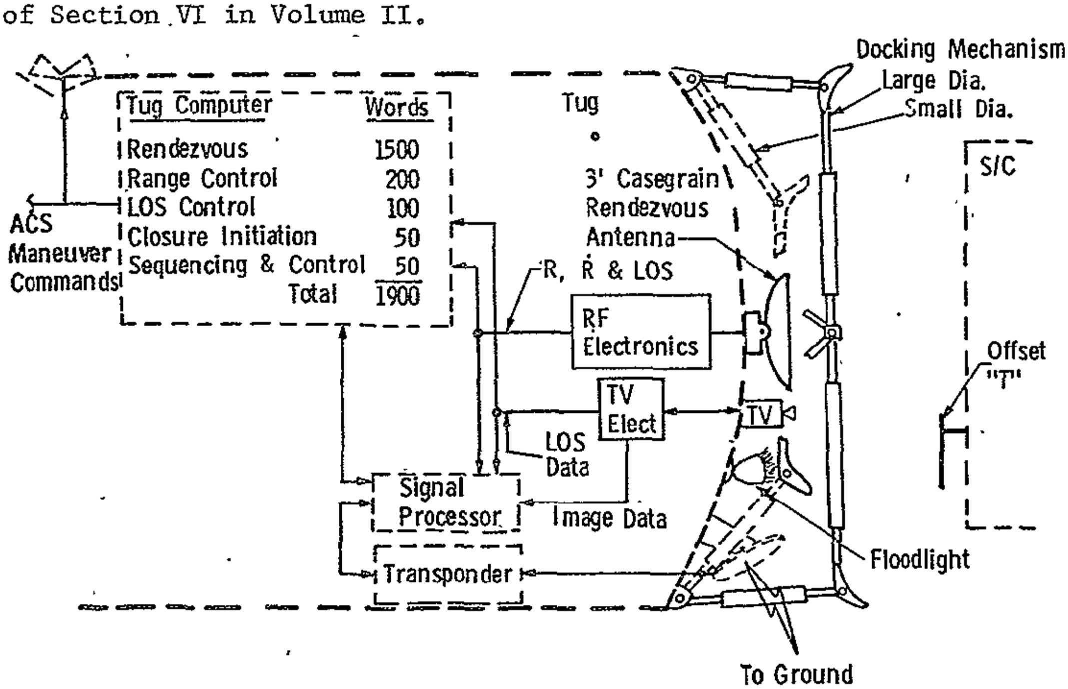

Figure III-1 Manual Candidate Configuration

The weight and power of the hardware components comprising this configuration are summarized below.

	Weight Kg (Lb)	Power Watts
RF Antenna	18.6 (41)	-
RF Electronics & Transmitter	15.4 (34)	275
TV TV Electronics	9 (20)	12
MDAC Docking Mechanism	252 (556)	Neg

The manual and hybrid configurations purposely involve man in the decision making process and in the vehicle control itself. Consequently, an effective and high bit rate ground link is required to insure a continuous coverage and as fast a response system as is possible. The key elements of the ground operations are illustrated in Figure III-2.

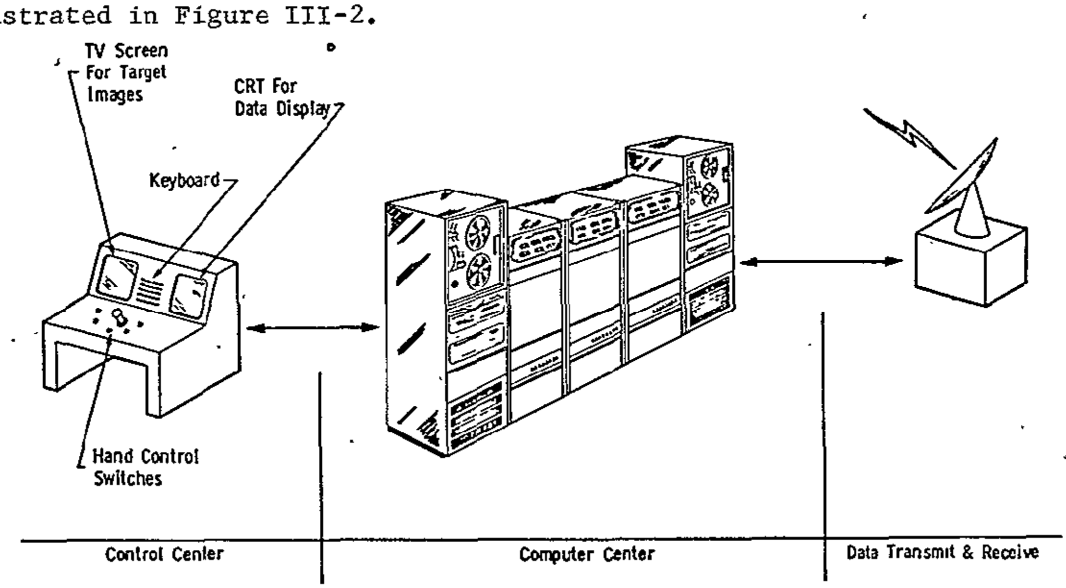

Figure III-2. Manual Candidate Ground Operations

The control center console will display visual data on a screen and formatted digital data (range, range rate, etc.) on a CRT. The data formatting, done in the ground computer, may also provide corridors of acceptable conditions to expedite performance monitoring by ground controller. An input to the Tug

vehicle command system can be provided from a keyboard/display. Hand controls will be provided for manual translation and rotation commands. Mode switches and monitoring lights will also be provided.

The computer complex will be the interface from the downlinked data to the control center. It will buffer, process and format data.

The downlink data rate is assumed to be the current Tug rate of 50 kbs. This does place an undesirable constraint on image picture refresh rate (on the order of seconds). It is recommended that some data compression of imaging data be done onboard and an image recreated in the ground computer as one means of improving this response time. See Part B of Section VI in Volume IV for further discussion of data compression.

An estimate of the span times and approximate dollars required in arriving at a developed manual rendezvous and docking system are provided in Figure III-3. No specific dates are given. Approximately the same tasks and phasing would be required regardless of the vehicle for which it is being designed.

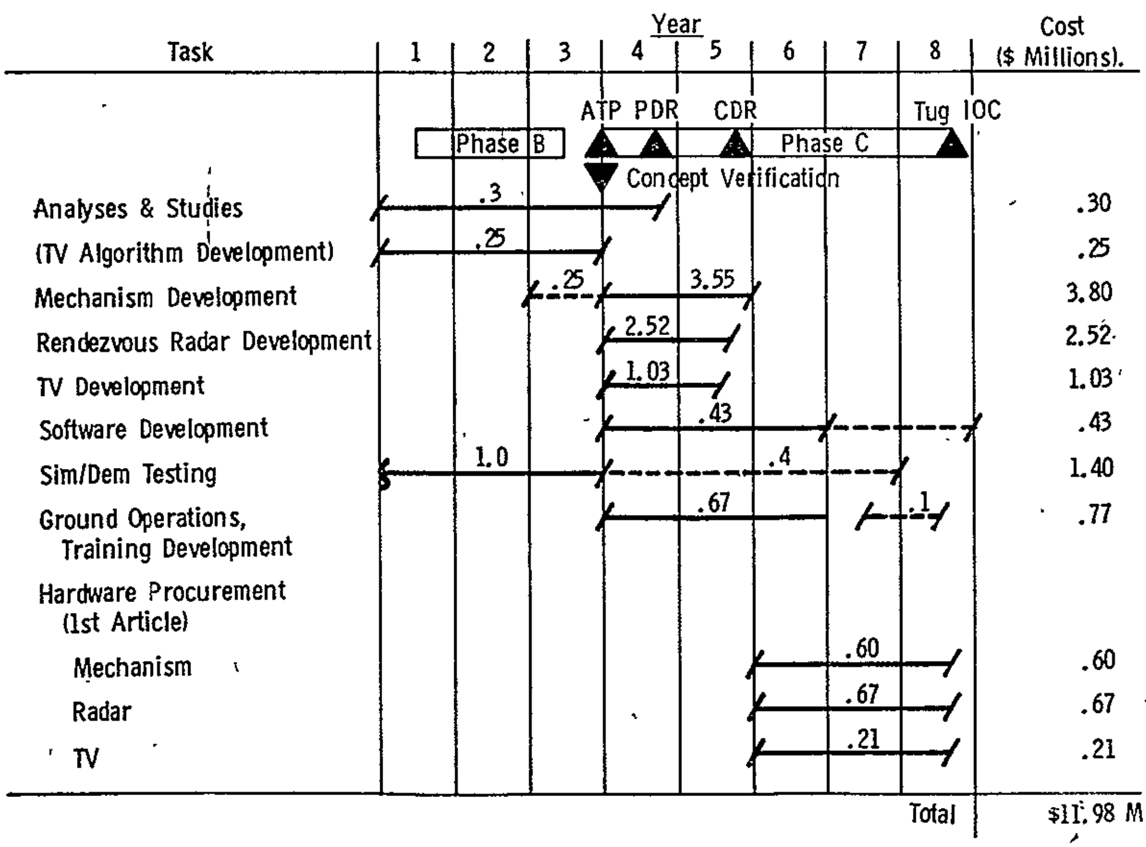

Figure III-3. Cost and Schedule - Manual Configuration

One unique characteristic of the manual development program is the front end effort to determine feasibility of realiably generating rendezvous and docking parameters exclusively from imaging information. Such effort has been proposed to NASA by MMC independent of this study and some initial work already done. This effort appears promising and should be continued.

Simulation/demonstration testing is also a key element in the manual concept verification as many of the performance parameters cannot be determined credibly without man performing his role under as realistic a set of conditions as is possible. The simulation/demonstration effort continuing after concept verification at ATP is in support of hardware development software development and eventually procedures development and training.

B. AUTONOMOUS CONFIGURATION

The autonomous configuration represents the other extreme in autonomy. It was presumed this configuration would be able to complete the entire sequence of rendezvous and docking with no ground control, or even ground monitor. The strategy below reflects that autonomy.

1) The sequence begins with ranging sensor acquisition at 23 km (12.5 n mi).
2) Ranging sensor data is used to perform terminal rendezvous from 23 km (12.5 n mi) to stationkeeping at the inspection range of 30 m (100 ft) while the ground monitors a TV image, if provided. Tug attitude is controlled from LOS data while position (translation maneuvers) is controlled from LOS rates and range data.
3) A preprogrammed lateral translation is commanded to initiate the inspection orbit. The vehicle continues to automatically track the target from LOS data.
4) Range and LOS data from skin tracking (or 4π steradian coverage reflectors) is used to command +X thrusting to maintain a constant orbit radius.
5) The inertial attitude of the docking port is assumed to be known. It will be stored in the Tug computer. The direction of the inspection orbit will be defined so as to fall within the

field of view of the docking port ranging sensor cues. When the docking port cues; e.g., a unique pattern of reflectors, is sighted (recognized from the unique pattern, or the unique signal returning as in the case of RF), a stationkeeping mode will be assumed and the original orbital velocity removed. Should the docking port not be sighted, the stationkeeping mode will still be accomplished to achieve coalignment of the Tug, but will use the stored inertial attitude of the target rather than any external cue. This is to avoid the unnecessary propellant usage of repeated searchings until the ground can evaluate the anomalous condition. If ground contact is prohibited, this is not acceptable, of course. Continuing orbital inspections of different inclination may have to be pursued until sensor contact is made.

6) On verification of docking port sighting, the Tug will calculate the target's attitude.
7) It will then compare that with Tug attitude and compute translation maneuvers to align the docking port axes.
8) The maneuver is executed. LOS tracking of target will be maintained during this maneuver. Target attitude will be recalculated each TBD seconds during the maneuver and a new relative "position-to-be-gained" computed until the correct desired inertial attitude is achieved.
9) When the vehicle's axes are satisfactorily coaligned, a closing velocity of .3 m/sec (1 fps) is initiated with a predetermined thrust-on-time. Range rate data will be used to trim it.
10) As the vehicle closes, LOS pointing will be maintained. Target attitude will be recalculated once each TBD seconds and translation corrections commanded to keep the docking axes coaligned (as in Steps 7 and 8).
11) Target attitude computations and translation corrections will cease when the target cues exceed the FOV of the sensor; $\sim$ 3 m (10 ft) for a 15 m (5 ft) attitude cue pattern and a 30 deg FOV. LOS tracking will be maintained until the last foot before docking.

12) Docking occurs; spacecraft attitude control is deactivated.

13) Mechanism contact monitoring is conducted.

14) Hard latch is commanded.

The non-impact configuration follows Steps 1 through 8 above. For Step 9 and subsequent steps the following are applicable:

9) When the vehicle's axes are satisfactorily coaligned, a closing velocity of .15 m/sec (.5 fps) is initiated with a predetermined thrust-on-time. Range rate data will be used to trim it.

10) As the vehicle continues to close the -X jets will be fired to slow the range rate along a predetermined range vs range rate profile until the range rate goes to zero when the range is $\sim$ 1.5 m (5 ft). LOS pointing and lateral translations will continue at this station-keeping distance, based on spacecraft attitude and relative lateral position data.

11) On initiation of a preprogrammed signal, the steerable boom (STEM) is deployed and initiates acquisition of the docking port by sensor.

12) On receipt of a signal indicating acquisition, the STEM is steered to a point at the port and while continuing to track, extends at a rate of $\sim$ 1.27 cm/sec (1/2 in/sec). The extend rate may be slowed somewhat as range decreases.

13) The probe extends until contact is made.

14) At this time the probe is slowly retracted at .254 cm/sec (1/10 in/sec) or .15 m/min (1/2 ft/min).

15) When soft contact is achieved, sensors will be actuated that initiate the hard latch sequence.

16) Both vehicles remain inertially stable until hard contact is made at which time the spacecraft control system is deactivated.

The candidate systems that were configured that accomplish these operations within the established requirements are shown below in Table III-4.

Twenty-four autonomous rendezvous and docking configurations were defined, but, as in the case of the manual configuration, they are made up basically of

Candidate	Sensor	Docking Mechanism	Weight Kg (lb)			Power	
			Mechanism	R&R Sensor	TV / Lights	Sensor	TV
A1	GaAs SLR	MDAC	252(556)	25(55)	-	40	-
A2		MMSE	440(970)	25(55)	-	40	-
A3		Non-Impact	241(531)	25(55)	-	40	-
A4	GaAs SLR And TV	MDAC	252(556)	25(55)	9(20)	40	12
A5		MMSE	440(970)	25(55)	9(20)	40	12
A6		Non-Impact	241(531)	25(55)	9(20)	40	12
A7	CO_2 Laser (Noncooperative)	MDAC	252(556)	22.7(50)	-	200	-
A8		MMSE	440(970)	22.7(50)	-	200	-
A9		Non-Impact	241(531)	22.7(50)	-	200	-
A10	CO_2 Laser (Noncooperative) And TV	MDAC	252(556)	22.7(50)	9(20)	200	12
A11		MMSE	440(970)	22.7(50)	9(20)	200	12
A12		Non-Impact	241(531)	22.7(50)	9(20)	200	12
A13	Rendezvous Radar (Noncooperative) And TV	MDAC	252(556)	34(75)	9(20)	275	12
A14		MMSE	440(970)	34(75)	9(20)	275	12
A15		Non-Impact	241(531)	34(75)	9(20)	275	12
A16	Rendezvous Radar (Cooperative) And TV	MDAC	252(556)	32(70)	9(20)	120	12
A17		MMSE	440(970)	32(70)	9(20)	120	12
A18		Non-Impact	241(531)	32(70)	9(20)	120	12
A19	Dual Mode Radar (Noncooperative)	MDAC	252(556)	36(80)	-	275	-
A20		MMSE	440(970)	36(80)	-	275	-
A21		Non-Impact	241(531)	36(80)	-	275	-
A22	Dual Mode Radar (Cooperative)	MDAC	252(556)	34(75)	-	120	-
A23		MMSE	440(970)	34(75)	-	120	-
A24		Non-Impact	241(531)	34(75)	-	120	-

Table III-4. Autonomous Candidate Summary

just eight unique sensor groups, and several of these are merely cooperative versions of non-cooperative sensors (cooperative requiring sensor cues and non-cooperative requiring none).

The estimated weights and power requirements are provided.

It may be noted that several sensor groups include a TV. It is assumed that this sensor will provide docking information (range, range rate, LOS and target attitude) during close-in operation as an alternative to using the primary sensor. The advantage is to avoid new development of a primary sensor and accompanying cue for close-in sensing when the function could be accomplished with a sensor that very likely will be present on the vehicle anyway, and some software algorithms implemented in a microprocessor in the TV electronics. The

non-impact docking, in particular, will require additional capabilities not feasible with any ranging sensors currently under development.

Evaluation of the autonomous candidates was performed in the same manner as the manual configuration. The candidate ratings and scores are shown in Table III-5.

The evaluation criteria was also the same, only the weighting changed slightly for several of the criteria

Development risk was weighed as a 3 rather than 2 because of the higher technology level, causing greater concerns on all aspects of developing that technology.

Mission operations was downgraded from a 2 to 1 as the autonomous candidates were purposely designed to require virtually no mission operations support.

Non-recurring cost was weighed a 3 instead of a 2 because of the higher technology level and the emphasis that it will place on the non-recurring development costs.

There are some points to be made relative to how these candidate ratings were derived that can be made here. Much of the general thoughts regarding the docking mechanisms and basic sensor characteristics discussed for the manual candidate are applicable here as well and will not be separated. There are some others, however, peculiar to an autonomous concept.

The major factor relates to the minimum range at which spacecraft attitude must be determined and what method is used to perform it. A decisive threshold exists between the two impact systems and the non-impact system. The impact systems require attitude data no closer than .3 m (10 ft), while the non-impact system must determine that data to .9 m (3 ft). It virtually requires an additional and different concept for most of the sensor groups. Consequently, the non-impact system makes a poor showing in such areas as development risk, mission success probability, spacecraft impact, and non-recurring cost.

In the case of the GaAs SLR sensor (no TV) additional spacecraft reflectors and new SLR capabilities will be necessary to provide the capability to derive attitude of the spacecraft and LOS data on a continuous basis at a .9 m (3 ft) range and within the existing 30° FOV.

Table III-5 Autonomous Candidate Evaluation

Evaluation Criteria	Weight	CANDIDATE																							
		A1		A2		A3		A4		A5		A6		A7		A8		A9		A10		A11		A12	
		R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V
Mechanism Weight	2	4	8	1	2	4	8	4	8	1	2	4	8	4	8	1	2	4	8	4	8	1	2	4	8
Sensor Weight	1	5	5	5	5	5	5	4	4	4	4	4	4	5	5	5	5	5	5	4	4	4	4	4	4
Power	1	5	5	5	5	5	5	5	5	5	5	5	5	3	3	3	3	3	3	3	3	3	3	3	3
Development Risk	3	4	12	4	12	3	9	3	9	3	9	2	6	2	6	2	6	1	3	2	6	2	6	1	3
Mission Success Probability	2	3	6	3	6	1	2	2	4	2	4	1	2	3	6	3	6	1	2	2	4	2	4	1	2
Software	2	3	5	3	6	2	4	2	4	2	4	1	2	3	6	3	6	2	4	2	4	2	4	1	2
Mission Operations Complexity	1	5	5	5	5	5	5	4	4	4	4	4	4	5	5	5	5	5	5	4	4	4	4	4	4
Servicing Potential	3	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	5	15
Spinning Spacecraft Compatibility	2	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	2	4
Spacecraft Impact - Structure	3	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	4	12
Spacecraft Impact - Cues	2	2	4	2	4	1	2	2	4	2	4	1	2	3	6	3	6	2	4	3	6	3	6	2	4
Ground Operations - GSE	1	2	2	1	1	2	2	2	2	1	1	2	2	2	2	1	1	2	2	2	2	1	1	2	2
Recurring Cost	2	3	6	2	4	3	6	3	6	2	4	3	6	2	4	1	2	2	4	2	4	1	2	2	4
Nonrecurring Cost	3	3	9	4	12	2	6	2	6	3	9	1	3	2	6	3	9	2	6	1	3	2	6	1	3
TOTAL		94		85		85		82		73		75		83		74		75		74		64		70	
Docking Mechanism		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact	
Sensor Group		GaAs SLR						GaAs SLR TV						CO_2 Laser (Noncoop)						CO_2 Laser (Noncoop) TV					

Evaluation Criteria	Weight	CANDIDATE																							
		A13		A14		A15		A16		A17		A18		A19		A20		A21		A22		A23		A24	
		R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V	R	V
Mechanism Weight	2	4	8	2	2	4	8	4	8	1	2	4	8	4	8	1	2	4	8	4	8	1	2	4	8
Sensor Weight	1	2	2	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	3
Power	1	3	3	3	3	3	3	4	4	4	4	4	4	3	3	3	3	3	3	4	4	4	4	4	4
Development Risk	3	2	6	2	6	1	3	2	6	2	6	1	3	4	12	4	12	3	9	4	12	4	12	3	9
Mission Success Probability	2	2	4	2	4	1	2	2	4	2	4	1	2	3	6	3	6	1	2	3	6	3	6	1	2
Software	2	2	4	2	4	1	2	2	4	2	4	1	2	3	6	3	6	2	4	3	6	3	6	2	4
Mission Operations Complexity	1	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5
Servicing Potential	3	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	5	15	3	9	2	6	5	15
Spinning Spacecraft Compatibility	2	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	2	4	4	8	4	8	2	4
Spacecraft Impact - Structure	3	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	4	12	3	9	3	9	4	12
Spacecraft Impact - Cues	2	4	8	4	8	2	4	2	4	2	4	1	2	3	6	3	6	2	4	2	4	2	4	1	2
Ground Operations - GSE	1	2	2	1	1	2	2	2	2	1	1	2	2	2	2	1	1	2	2	2	2	1	1	2	2
Recurring Cost	2	5	10	4	8	5	10	5	10	4	8	5	10	3	6	2	4	3	6	3	6	2	4	3	6
Nonrecurring Cost	3	1	12	5	15	1	3	4	12	5	15	1	3	3	9	4	12	2	6	3	9	4	12	2	6
TOTAL		89		80		74		87		79		76		91		82		82		91		82		82	
Docking Mechanism		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact		MDAC		MMSE		Non-Impact	
Sensor Group		Rend. Radar (Noncoop.) TV						Rend. Radar (Coop.) TV						Dual Mode Radar (Noncoop.)						Dual Mode Radar (Coop.)					

NOTES: Weight, 1 = less important; 3 = more important
Rating, 1 = poor; 5 = good
V = value (or W x R)

The second sensor group has employed a TV to perform that same attitude determination from 3 m (10 ft) on into .9 m (3 ft). This is a new role for a TV and will require considerable development of the software algorithms and spacecraft cues. There is still a concern as to feasibility of such an approach. Its advantage and the reason for maintaining it as a candidate comes from the fact that a TV will probably be aboard the Tug anyway and by using it, along with software algorithms, the necessity of further development of the prime ranging sensor and its new reflectors is not necessary. All candidates using the TV in this manner, however, do reflect concerns, specifically in the ratings for risk and non-recurring cost.

The same rationale exists for all other candidates using a TV, in fact, even greater concern is involved with the rendezvous radar candidates (A13 to 18), as the TV must provide all data necessary from 30 m (100 ft) on in, rather than 3 m (10 ft) as for the other candidates.

The remaining sensor groups--the CO_2 laser by itself and the dual mode radar--probably provide the lowest risk in the area of close-in operation. Some design of a separate spacecraft cue for target attitude determination has been done for the CO_2 laser. The dual mode radar can achieve attitude determination at closer ranges using just the one set of cues because of closer reflector spacing and faster response than the GaAs SLR's attitude determination technique has.

The three highest ranked candidates from Table III-5 are shown in Table III-6.

Table III-6. Highest Ranked Autonomous Candidates

Rank (Score)	Sensors	Mechanism
1 (94)	GaAs SLR A1	MDAC Square Frame
2 (91)	Dual Mode RF Radar (Non-cooperative) A19	MDAC Square Frame
3	Rendezvous Radar and TV A13	MDAC Square Frame

The top ranked system relies on the GaAs SLR for all phases of the rendezvous and docking, and uses the MDAC square frame docking mechanism. Within the required 23 km (25 n mi) acquisition range, the GaAs SLR provides a light and accurate sensor with demonstrated capability to more than adequately meet all measurement requirements. Only slightly lower ranked are the dual mode RF-RADAR configuration, and a modified Apollo RADAR coupled with a TV docking system that relies on automated algorithms to derive control motions. Both of these approaches require less completely proven developments than the SLR. There is risk involved with the latter two candidates, particularly for the autonomous docking with a TV and its algorithms, about which concerns were expressed earlier. Hardware development and costs for the third candidate, by itself, is undoubtedly the lowest of all three, however, the TV algorithms concern offsets this considerably.

The highest ranked autonomous candidate, depicted in Figure III-4, is a relatively simple one. The mechanism is the MDAC square frame impact type; the same as the manual. The sensor is just the GaAs scanning laser radar. It requires an array of corner reflectors in order to detect the docking port and determine S/C attitude. The S/C attitude determination array may be as large as 1.5 m (5 ft) across since S/C attitude data is not required closer than 3 m (10 ft) for an impact docking.

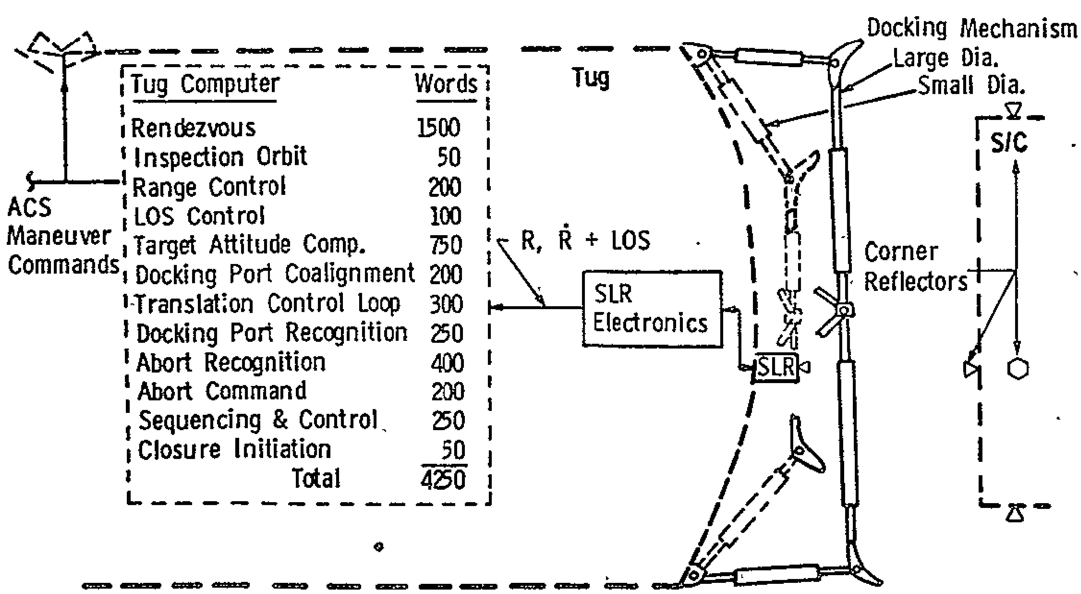

Figure III-4. Autonomous Candidate Configuration

Considerable software is required in the Tug computer since all vehicle commands must be generated onboard. The target attitude determination computation and generating vehicle commands from the data is the most significant software addition over the manual configuration. Another unique software addition is the abort detection and correction routines. These routines represent the highest risk in successful development and also in providing confidence in ability to detect and correct for all feasible failure modes. A detailed description of all software routines is provided at the end of this section.

The hardware weights and power for this candidate are:

	Weight Kg (Lb)	Power
Docking Mechanism	252 (556)	400 Watts
GaAs SLR	18 (40)	
SLR Electronics	6.8 (15)	

There is no ground operations required for the autonomous configuration, however, in all reality the Tug will probably carry a TV for inspection purposes and a ground monitoring activity could very well exist on initial flight similar to that depicted for the manual case in Figure III-2.

An estimate of the span times and approximate dollars required in arriving at a developed autonomous system is depicted in Figure III-5. No specific dates are given. The schedule of development would be much the same regardless what vehicle it was designed for.

The software development shows a significant increase over the manual case because of the increased software required.

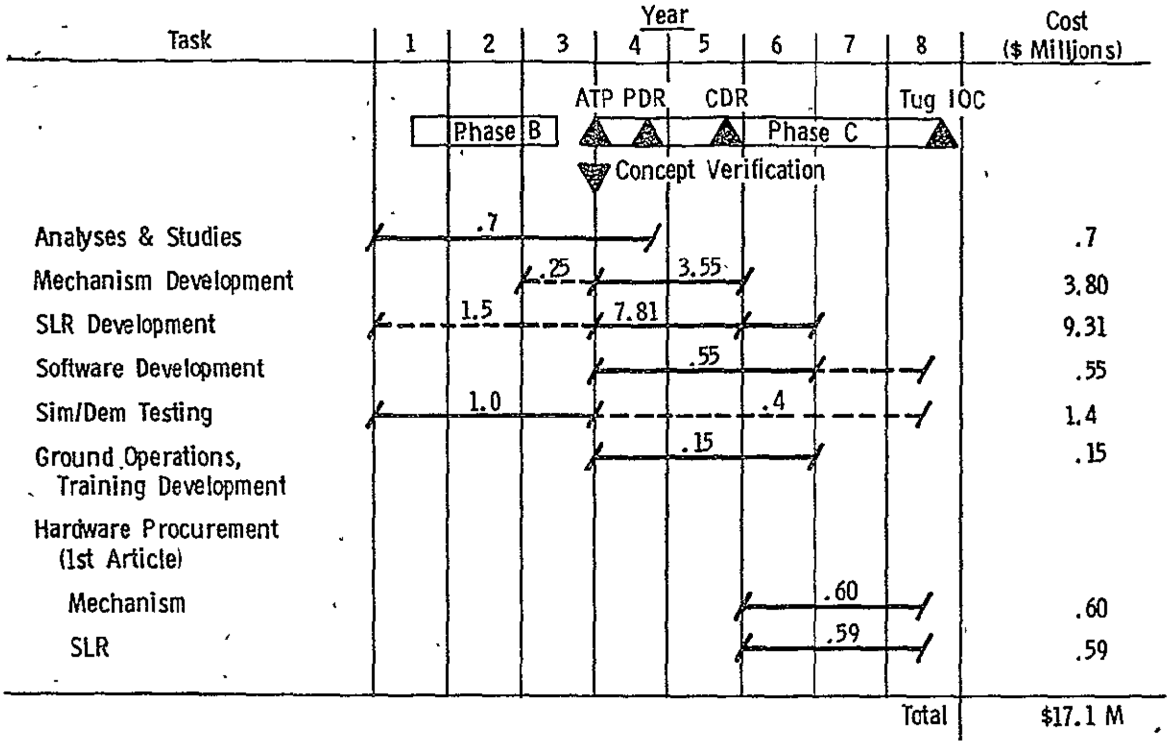

Figure III-5 Autonomous Candidate - Cost and Schedule

Software Estimates -

Terminal Phase Rendezvous (1500 words) - This element of the software implements the proposed proportional navigation scheme of rendezvous. It starts at the acquisition range of 28 km (12.5 nm) and concludes at the inspection orbit of ~ 30 km (100 ft). This is an autonomous phase. The software includes filtering as well as logic related to developing commands for the lateral and longitudinal ACS thrusting. It will not include the attitude control loop phase plane logic itself, which is a part of the baseline Tug software. A similar proportional navigation implementation on the Mars Surface Sample Return Mission estimated the software requirements for the above functions at 1000 words. To provide some margin and to account for navigation from the completion of the proportional navigation phase at several hundred feet down to 30 m (100 ft), an additional 500 words has been added for a total of 1500. That includes instructions and memory for parameters and variables, such as gains, etc. It was pointed out in the rendezvous phase analysis, Section II.D.1, that the proportional navigation algorithm by itself develops large uncertainties in the final kilometer or so, consequently it was recommended an independent algorithm be used for the phase from several hundred meters on in to the inspection orbit range.

Inspection Orbit Initiation (50 words) - This is presumed to be a simple algorithm of which less than 25 words are allocated to the instructions required to achieve a lateral velocity of given value. Variables in the equation are mass, orbit radius, etc. The remaining 25 words are set aside for storage of constants, variables and thrust times for a library of selected orbit periods.

Automatic Range Control Command (200 words) - This routine generates + or - x translation commands in the form of position errors, to maintain either (1) a constant range (inspection orbit), (2) a constant range rate (impact type closure), or (3) a range rate vs range profile; for non-impact type closures for example. The majority of the software would be associated with the latter and with the memory required to store the parameters for several different profiles. This routine accepts sensor range and range rate data. It's output is to the translation command control loop described below which performs the equivalent of the rotation attitude control loop phase plane logic.

Automatic LOS Control Command (100 words) - This routine, like that above, generates translation commands but in a lateral direction only (± y and z) to maintain a given LOS angle to the target. It accepts LOS, LOS rate, and range data from the sensor and it outputs a translational position error correction command. A large part of the software will be filtering, some of it predictive, necessary to accomplish the position error nulling in an optimum manner, minimizing ACS usage and overshoots. This routine will also provide any necessary coordinate transformation from sensor to ACS jet reference frame. Some memory will be set aside for the filters, gains and constants. Again the translation control phase plane control loop is not a part of this but rather handled as a general purpose routine as described below.

Target Attitude Computation (750 words) - In the development work by ITT and MSFC for the GaAs SLR, the equations were defined for attitude computation. The estimate of 750 is based on those equations with some margin added. This routine utilizes GaAs outputs. Its output, in turn, is an internal one providing an inertial attitude in a space reference frame to the following two routines.

Docking Port Coalignment Maneuver Computation (200 words) - This routine implements the equations that take the Tug position vector and the target vehicle position vector from the routine above, determines the difference between the two, and transforms that position error into the Tug ACS jet reference frame. The resulting position errors are inputs to the lateral translation command control loop described below.

This routine, along with the one above, is repeated in sequence at least once each (TBD) seconds in order to successfully coalign the two vehicles docking ports. Some filtering is presumed to smooth and optimize the process. The software estimate is based on similar maneuver routines in Titan IIIC digital autopilot, which range from 28 to 125 words, not including filter terms in the loadable memory. Allowing for some margin, a total of 200 words seemed more than adequate.

Translation Command Control Loop (300 words) - This is really three independent loops, one for each axis, of ~ 100 words each, though there are common elements since the three axes will be processed in sequence. The software for each loop is concerned basically with implementing the phase plane control logic, i.e., the rate and position switching lines. The output is varying ACS jet on-times depending on the vehicles position with respect to desired position and rate. TIIIC digital autopilot coast state software was 370 words.

Docking Port Recognition (250 words) - This routine implements a series of equations, or decision blocks, that process, or interrogate if you will, the SLR signal returns. The process must determine when the docking port is sighted by discerning the presence of the four target attitude cues. The process must differentiate the target attitude cues from other corner reflectors on the S/C by the unique orientation of the 4 cues. It must be capable of concluding this

routine without error or false signals from all possible orientations of the two vehicles. A number of contingency situations must be built into this routine. A larger than usual margin is provided because of the possible unknowns.

Abort Recognition Program (400 words) - This routine is as large as the number of potential failures that can be anticipated. Since this depends on detailed design, a large uncertainty still exists as to the content of this routine. Consequently, a reasonably large allocation has been set aside for now. This routine will have to identify Tug failures related to rendezvous and docking hardware failures, such as sensors and latches, as well as failure to perform operational functions or sequences. Inputs are required from all Tug rendezvous and docking system hardware as well as other subsystems necessary to ascertain the failures above. The routine's outputs are to the abort command routine described below. Malfunction detection logic for the TIIIC inertial guidance system alone was over 300 words.

Abort Command (200 words) - This routine will receive any one of a number of different "failure" indications from the previous routine. Dependent on the indication, a previously determined sequence will be initiated and carried out by this routine. It will initiate the actions such as closure termination, inspection termination, collision avoidance, etc., and perform whatever monitoring is necessary or possible to insure successful abort accomplishment. At least six different abort sequences are anticipated with a minimum of 30 instructions and parameters each.

Sequencing and Control (250 words) - This routine will initiate, monitor where necessary, and terminate all operations in the entire autonomous rendezvous and docking sequence. Involved are: timing operations, relays, latches and power sequencing, and control. Most other software routines, including the abort monitor and command subroutines, are brought into and out of play by this routine. Executive control and basic computer timing will not be a function of this routine.

Closure Initiation (50 words) - This is a simple routine that calculates the ACS jet on-time for a predetermined closure velocity. It is a simple equation dependent on Tug mass, velocity desired, etc. Most of the software is for a library of the variable parameters.

C. HYBRID CONFIGURATION

The hybrid configuration was derived in a different manner than the manual and autonomous candidates were earlier. Rather than contriving a large number of potential candidates from which the best are selected, the hybrid is a single candidate composed of strategies and hardware considered the best, based on knowledge obtained from the earlier manual and autonomous candidate selection process.

The hybrid configuration was derived out of two basic concerns:

1) The manual configuration is dependent on continuous TV transmission during the entire phase. Loss of that data can very likely result in loss of the mission. In addition, the data rate constraints provide a ground image update frequency that results in normal operation bordering on marginal operation from a risk standpoint. There is considerable concern about feasibility of manually recognizing and reacting to abort conditions.

2) The second concern relates to the autonomous configuration. There is, first, a concern merely from the standpoint of the additional technology required to accomplish, via hardware and software, the many complex tasks. However, at this time it does appear to be a feasible development. The real concern is developing reliable, autonomous techniques for (1) determining that each phase has been accomplished in a satisfactory manner and is ready for the next step, (2) identifying an anomalous condition when it occurs, and (3) performing fail safe actions that can recover from a failed condition reliably.

Based on these factors the implementation for the hybrid was to select a system that performs most of the operations autonomously while the ground monitors and evaluates each step of the sequence providing the necessary "go" or "no-go". The ground also has the capability of manually performing the entire sequence, thereby providing redundancy of a functional form. This is desirable since it provides protection against generic type of failures.

The system, then, is basically autonomous with manual control of sequencing. Where relatively complex autonomous tasks were identified in the autonomous configuration, however, such as docking port recognition, the task has been left to the man on the ground. The detailed sequence of events for this impact docking configuration is:

1) The sequence starts at automatic target acquisition at 23 km (12.5 n mi).

2) Rendezvous to the stationkeeping point is accomplished autonomously using ranging sensor range, range rate, and LOS data. The ground monitors this phase on TV.

3) Ground monitors satisfactory accomplishment of stationkeeping and provides a "go" for orbit inspection (possibly selecting an optimum orbit from a presotred library of them).

4) The orbit inspection is computed and initiated onboard based on range and prestored desired orbit period.

5) LOS is being maintained autonomously throughout.

6) The docking port is sighted manually.

7) When it is within range of the onboard attitude determination capability, the orbit inspection is stopped by ground command, the initial orbit insertion Δ V is automatically removed, and stationkeeping is assumed.

8) The Tug ranging sensor computes the target attitude with respect to the Tug and displays it on the ground.

9) After a "go" from the ground, the maneuver required for X-axis coalignment is calculated and executed in the form of translation commands, with LOS to the spacecraft maintained automatically. The ground monitors the maneuver and can take over in the event of anomalous conditions.

10) After coalignment is accomplished, another "go" from the ground initiates the closure phase.

11) A closing V of 1 fps is imparted using a prestored +X jet on-time. This is monitored onboard and trimmed automatically using sensor range rate data.

12) LOS to the spacecraft is maintained until approximately .3 m (1 foot).

13) The Tug continues to compute target attitude to verify vehicle X axes coalignment.

14) If lateral position error is detected, translation commands are computed and executed to maintain coalignment automatically until target attitude information is lost at approximately 3 m (10 ft).

15) Throughout this phase the ground is monitoring the closure on TV (both image and range, range rate, and LOS data from ranging the sensor) and has the capability to take over from the Tug control system and complete the closure manually at any time.

16) Docking occurs; spacecraft attitude control is deactivated.

17) Mechanism contact omintoring is conducted.

18) Hard latch is commanded.

The hardware elements selected for the hybrid system are:

- o GaAs SLR
- o TV
- o Impact Docking Mechanism (MDAC square frame)

The rationale for that selection is as follows:

Ranging Sensor - The GaAs SLR was chosen because it can autonomously provide both ranging data and target attitude information with basically the same hardware; only the cues are expanded and some software is added. The RF candidate utilizes a different concept altogether for attitude determination, adding hardware development. The SLR is also relatively light and low-power. The extended range capability the CO_2 SLR could provide is not required in the present scenario that show acquisition at 23 km (12.5 n mi). Utilization of the TV for ranging is not practical due to ranging limitations. It is more useful in a backup role for docking only.

Some development has already been done on the GaAs SLR.

Visual Sensor - A TV is provided for monitoring the autonomous operations and furnishing a capability for manual control of the vehicle in a backup mode.

Docking Mechanism - An impact mechanism was selected, as it was for the other candidates, because of the additional complexity in the station-keeping control mode and steerable probe control of a non-impact device. Servicing is, of course, not readily achievable with the impact system, but for this study was not a requirement. The MDAC mechanism is currently recommended as it is reasonably lightweight and shows some growth potential to a servicing role and to spinning spacecraft retrieval.

The hybrid configuration is depicted in Figure III-6. It is much the same as the autonomous candidate in that it utilizes the same docking mechanism,

the same ranging sensor - GaAs SLR - and the same basic ranging cues. A TV for manual backup control and decision making has been added, however, this has allowed some reduction in software required; specifically the abort recognition, abort command routines and the docking port recognition routine. A detailed description of software routines for all configurations is provided under the autonomous configuration description, Part B of this section. Refer to the applicable routines described in that section.

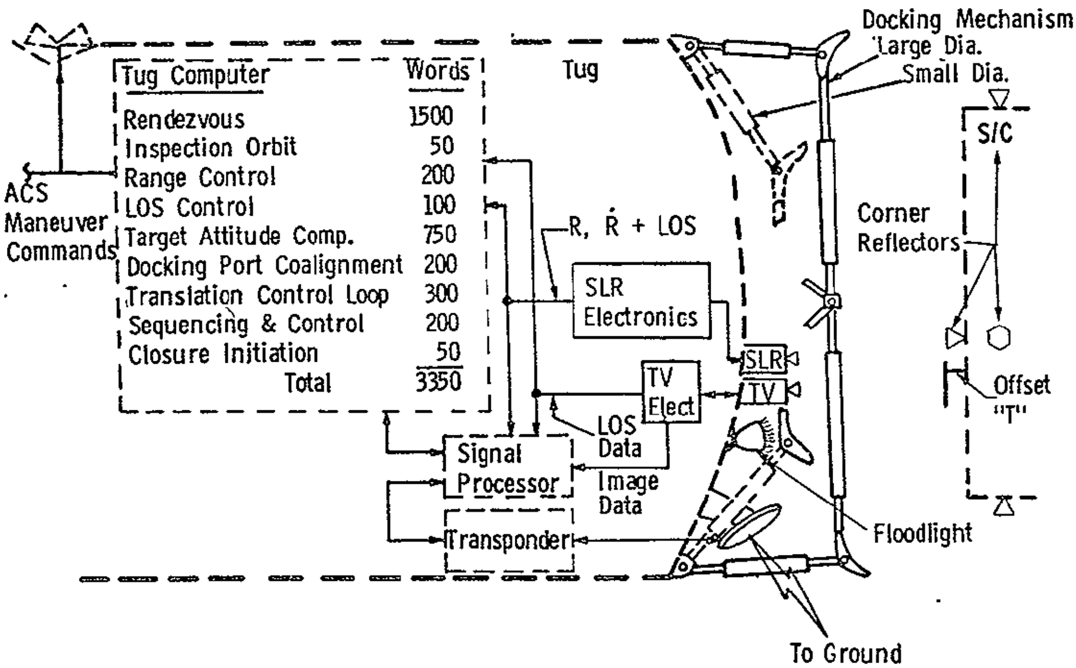

Figure III-6. Hybrid Candidate Configuration

The hardware weight and power data is summarized as follows:

	Weight Kg (Lb)	Power (Watts)
Docking Mechanism	252 (556)	
GaAs SLR	18 (40)	40
SLR Electronics	6.8 (15)	
TV TV Electronics	9 (20)	12

The estimated span times and dollars for the hybrid candidate development are shown in Figure III-7. These are really a composite of the pertinent efforts

from the manual and autonomous development programs. The simulation/demonstration test program is an area of major importance since the hybrid system embodies a relatively high degree of hardware and software technology for onboard operations, as well as all the ground control operations for the manual configuration.

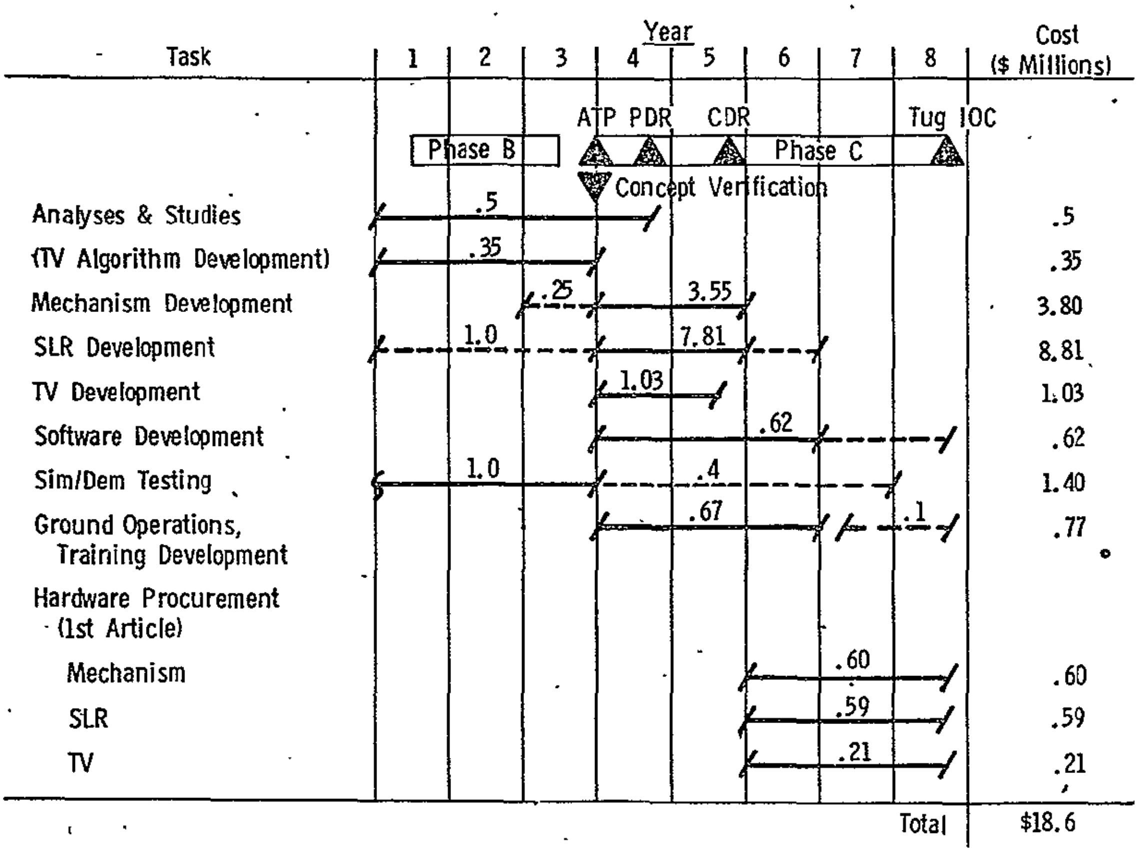

Figure III-7. Hybrid Candidate - Cost & Schedule

The emphasis to be placed on the hybrid development, then, is not so much simulation/demonstration dollars, but rather scheduling of an early and expedient simulation/demonstration program that will allow for better planning of the complex hardware and software development tasks that follow.

IV. SIMULATION/DEMONSTRATION DEFINITION

A remote rendezvous and docking capability is highly desirable for the STS era. This section deals with those areas of development where simulation/demonstration testing appears necessary and beneficial. The approach to defining a simulation/demonstration program is discussed in this section. The factors considered in selecting test facilities and scheduling the tests, as well as preliminary analyses and long-lead developments required, are also addressed.

A. INTRODUCTION

A primary goal of the simulation/demonstration test definition was to maximize the use of existing MSFC facility capabilities. During the study a tour of these facilities was conducted and discussions were held with those MSFC personnel familiar with the facility operation and projected uses.

Tools were developed to assist in the facility screening and scheduling activity. A technical risk analysis was performed to assess the development status of each proposed test objective. Those tests in which a low confidence level existed were given a high priority and, where possible, were scheduled with the longest lead time. However, other factors impact the schedules. A matrix of tests and their predecessor requirements was prepared for use in scheduling. Predecessor rrquirements are those analyses, SRT tasks and other activities which must precede a given test. The results of these analyses, the test planning and schedules are presented in this section. However, the detailed simulation/demonstration test descriptions and plans may be found in Volume III of this report.

Facility selection for each test was based on several factors, also. A fidelity requirements assessment was performed to determine the simulation fidelity required for dynamics spacecraft, Tug, and visual representations. An assessment of the acceptibility of scaling for each test was also made. The results of these analyses are presented in this section with a facility modification plan presented in Volume III of this report.

The simulation/demonstration program described here is basically a phase "A" effort. The development activities are expected to produce a system design

for which a reasonable confidence level is established, with the technical risk reduced to the point that full development can be started.

A Shuttle flight test is recommended as a final system development following successful simulation/demonstration program. It seems feasible that this activity could be incorporated into the planned Shuttle Teleoperator Bay Experiment (TOBE objectives.

B. TEST REQUIREMENTS DEVELOPMENT

Test requirements were derived starting with a top-down functional flow. The flight phases encompassed by rendezvous and docking capability were identified. Those functions which must happen to accomplish rendezvous and docking were related to these phases. Tests were defined for each function on a one-

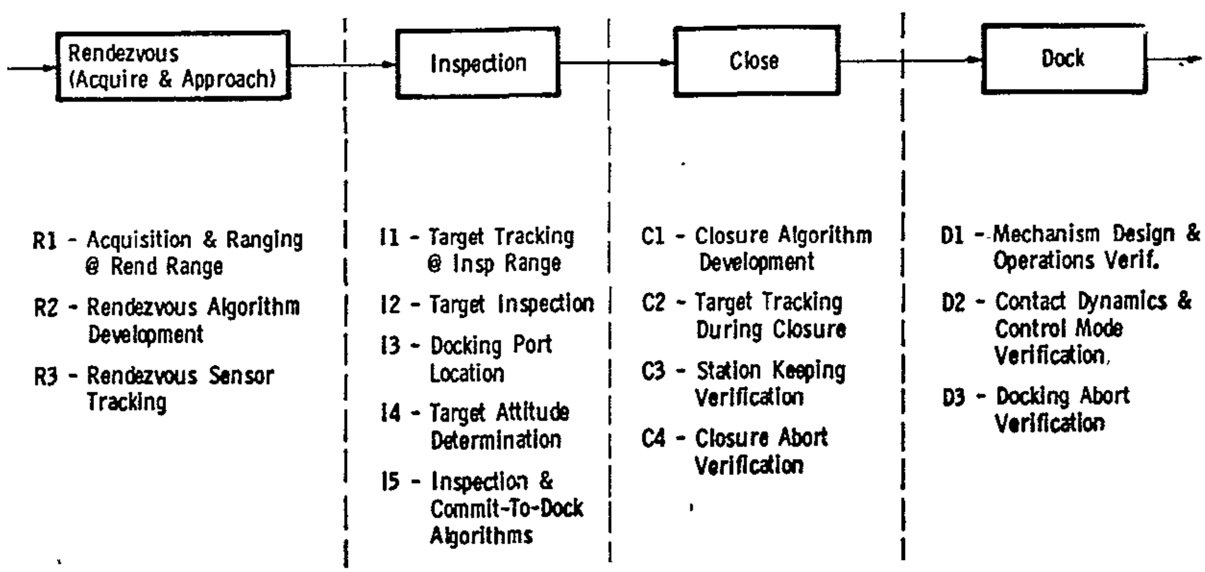

Figure IV-1. Tests Provide End-to-End Functional Verification

Subscripts were applied to these tests to indicate either manual (M) or autonomous (A) system tests. Each test was ranked for priority risk with the test having the highest risk given a ranking of one (1). The priority risk numbers were based solely on technical risk or lack of confidence in development status.

The results of a fidelity and scaling assessment are presented in Table IV-1 with a ranking of zero (0) to three (3) for the fidelity categories analyzed.

Table IV-1: Fidelity and Scaling Requirements Select Facilities

Coded Ident. (Priority Risk)	Test Title	Scaling Accept-able	Spacecraft Con-fig.	Spacecraft Cues	Dynamics Tug	Dynamics SC	Visual Cele-Stial	Visual Light	Tug Sensor	Tug Mech	Tug SW	Tug Comm.	Total
	Rendezvous												
R1A(12)	Autonomous Acquisition, Tracking & Ranging At Maximum Range	No	1	2	2	0	1	1	3	0	1	0	11
R1M (3)	Manual Acquisition, Tracking & Ranging At Maximum Range	Yes	1	1	2	0	3	3	3	0	0	1	13
R2 (19)	Rendezvous Algorithm Verification	N/A	0	0	0	0	0	0	2	0	3	0	5
R3 (15)	Rendezvous Sensor Tracking - Autonomous	No	1	2	2	1	2	2	3	0	2	0	15
R3M (15)	Rendezvous Sensor Tracking - Manual	Yes	2	2	2	1	3	3	2	0	2	2	19
	Inspection												
I1A (14)	Automatic Target Tracking	No	1	3	2	1	1	1	3	0	2	0	14
I1M (6)	Manual Target Tracking TV	Yes	2	3	2	1	3	3	3	0	2	1	19
I2A (7)	Automated Target Inspection	No	1	3	2	1	1	1	3	0	1	0	13
I2M (22)	Manual Target Inspection	Yes	2	3	2	1	3	3	3	0	0	3	20
I3A (8)	Docking Port Identification Automated	No	1	3	2	1	1	1	3	0	1	0	13
I3M (5)	Docking Port Identification Manual	Yes	1	3	2	1	3	3	3	0	1	0	18
I4A (16)	Target Attitude Determination Automated	No	1	3	2	3	1	1	3	0	3	0	17
I4M (4)	Target Attitude Determination Manual	Yes	1	3	2	3	3	3	3	0	3	3	24
I5 (9)	Inspection & Commit-To-Dock Algorithm	N/A	2	1	2	2	0	0	1	0	3	0	11
	Closure												
C1M (20)	Closure Algorithms Verification	N/A	0	1	2	2	0	0	1	0	3	0	9
C2A (18)	Target Tracking During Closure Autonomous	No	1	3	3	3	0	0	3	0	2	0	15
C2M (17)	Target Tracking During Closure Manual	Yes	1	3	3	3	2	2	3	0	2	2	21
C3M (11)	Manually Achieve & Maintain Close-In Stationkeeping	No	2	3	3	3	2	2	3	0	2	3	23
C3A (2)	Automatically Achieve & Maintain Close-In Stationkeeping	Yes	2	3	3	3	2	2	3	0	2	0	20
C4A (1)	Closure Abort Procedures - Autonomous Operations	Yes	2	3	3	3	2	2	3	0	3	0	21
C4M (13)	Closure Abort Procedures - Manual Operations	Yes	2	3	3	3	2	2	3	0	3	3	24
	Docking												
D1 (10)	Latch Design And Operations Verification	No	2	0	3	3	0	0	0	3	0	0	11
D2 (21)	Dynamics Effects - Pre-And Post-Latch	No	3	0	3	3	0	0	0	2	0	0	11
D3 (23)	Docking Abort Procedures	No	3	0	2	2	1	1	0	0	2	0	11

Fidelity: 0 - None Required
1 - Low Fidelity
2 - Medium Fidelity
3 - High Fidelity

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A high total indicates a requirement for high fidelity in a general se
However, the driving requirements which select a given facility for a specific test are typically celestial scene fidelity and scaling acceptability, for example. An overview of the selected facilities by phase and candidate system (manual or autonomous) is presented in Figure IV-2.

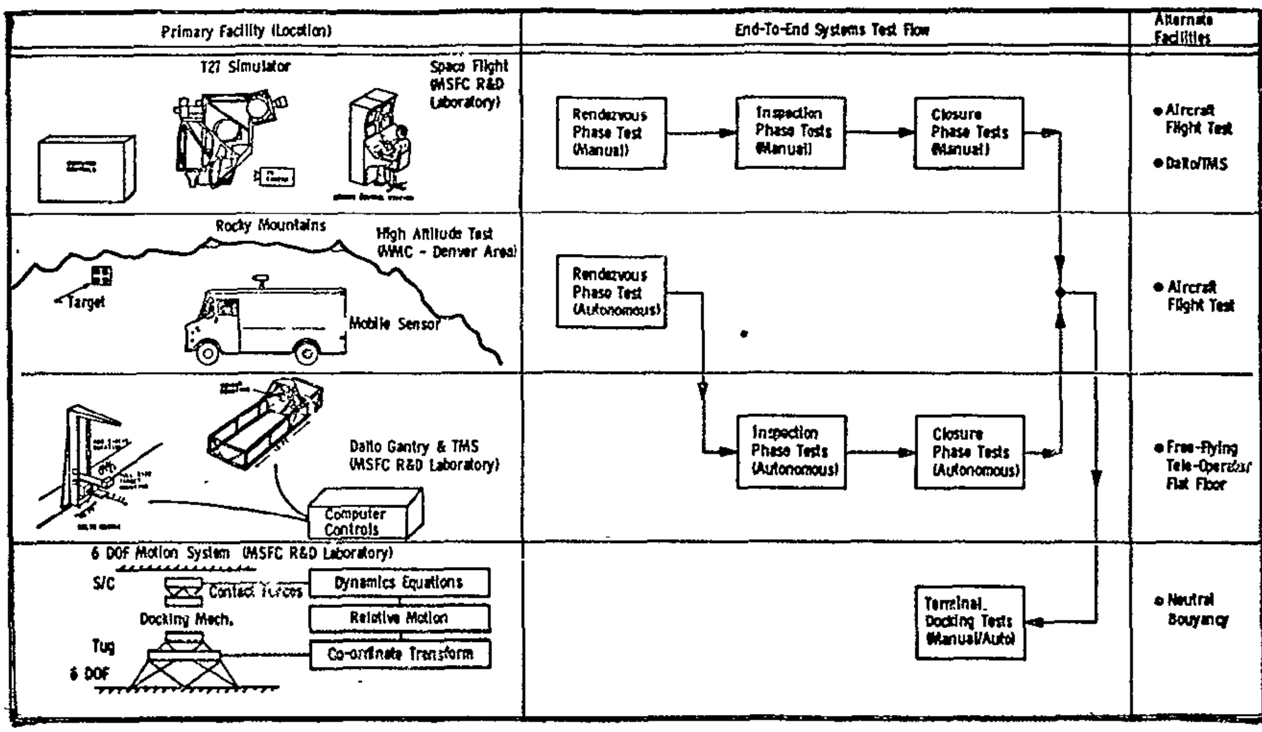


Figure IV-2. Autonomous & Manual Tests Have Differing Facility Requirements

The hybrid system is comprised of elements from the autonomous and manual candidate systems, and the tests are proposed to accompany those selected elements or subsystems. However, new interfaces exist in a hybrid system candidate as a result of bringing together these subsystems. This requires a control hierarchy in the system logic with capability for control handover from an autonomous element to a hybrid element, or vice-versa. This "best-mix" system has an advantage of inherent functional redundancy, but requires additional tests to validate the interfaces and control logic hierarchy.

R1M - Acquisition, Tracking & Ranging At Max. Range

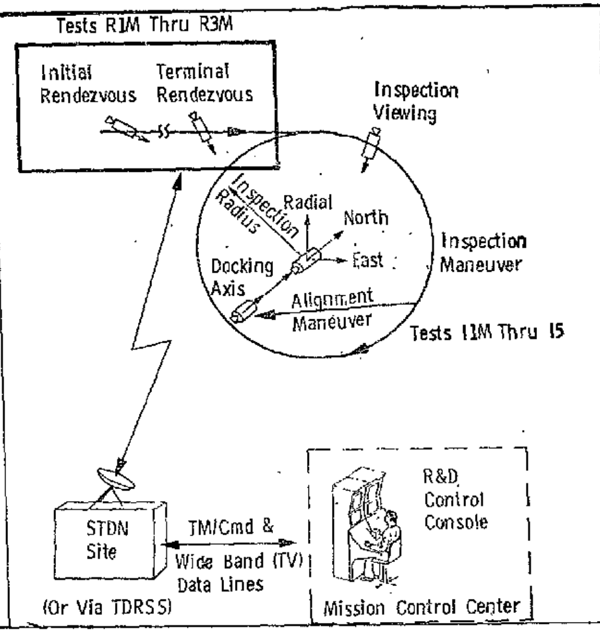
- New Applications Of Space-Proven Sensors
- New Mission Control Center Software
- Uncertainties Of Placing Man At Remote Control Station
- Uncertainties In Range Of TV And Lighting Effects

R2 - Rendezvous Algorithm Verification

- New Software Applications
- Required To Support Other Rendezvous Tests

R3M - Rendezvous Sensor Tracking

- New Application For Sensor/Software
- Extension Of Test R1M
- Defines Closure Rate Specifications
- Determines Data Link Loading & Delay Effects



I1M - Manual Target Tracking

- Reduced Range Requires More Stringent Controls
- Determines Lighting/Pointing Constraints
- Defines Range Determination Requirements On Sensor

I2M - Manual Target Identification

- Added Complexity Of Tracking And Maneuvering
- Define Inspection Range Specification
- Ascertains Need For Lights For Inspection
- Defines Maneuver Rate/ACS Propellant Usage
- Verify Line-Of-Sight (LOS) Angle Control Accuracy Specification

I3M - Docking Port Identification

- Determines If Additional Maneuvers Are Required
- Ascertains Need For Lighting To Locate Docking Port

I4M - Target Attitude Determination

- Determine Accuracy Of TA Determination Capability
- Refine Target Mounted Aid/Pattern Specification

I5 - Inspection And Commit-To-Dock Algorithm

- New Software Algorithm
- Required To Support Other Inspection Tests

C1 - Closure Algorithm Verification

- New Software (Onboard/Ground)
- Required To Support Other Closure Phase Tests

C2M - Target Tracking During Closure

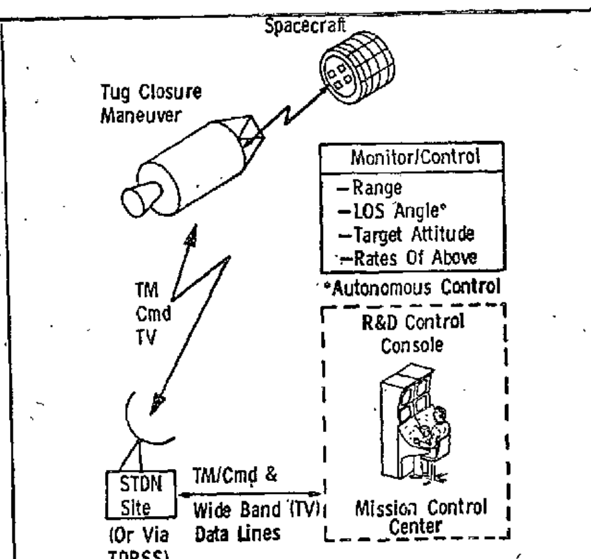
- Reduced Range → More Stringent Control
- Establish Closure Rate Specification
- Define Image Data Update Requirement
- Refine Minimum Range Requirements For Loss Of Sensed Data

C3M - Manual Stationkeeping

- New Application For Control Software
- Added Complexity - More Stringent
- Desirable For Abort Capability
- Establishes Station-Keeping Range Specifications

C4M - Closure Abort

- New Application Of Existing Technology
- Define Added TM Points For Decisions By Console Operator



D1 - Latch Design & Operations Verification

- New Hardware Design
- Establish Dynamics, Loads And Shock Attenuation Specifications
- Verify Range Of Lateral & Angular Misalignment Accomodations

D2 - Dynamics Effects - Pre-And Post-Latch

- Establish Tug ACS Control Mode Specification
- Refine Manual Control Interactions With Tug Control System
- Establish Spacecraft Interface Loads, Shock & Vibration Criteria Specification

D3 - Docking Abort

- New Application Of Existing Technology
- Define Additional TM Requirements For Decisions By Console Operator

Figure IV-3. Test Rationale Summary for Manual System Tests

FOLDOUT FRAME 1

FOLDOUT FRAME 2

C. TEST ELEMENT DESCRIPTION

The basic methodology in the test planning was one of limiting the number of variables which are introduced into a given test element at once. This is accomplished by a "building block" approach based on test complexity. For example, the initial inspection phase test verifies the capability of the sensor under test to perform ranging, LOS and target attitude at inspection range. The complexity of performing this same function while the Tug is maneuvering around the target is added for the second inspection phase test. Checkpoints along the way reduce the nu ber of variables and expedite the test flow. This allows verification of the first capability before introducing another "building block" of complexity; thus proceeding stepwise through the scenario.

The test elements described in the following paragraph are subdivided into supportive test rationale and facility selection for each defined test. A further subdivision is made by manual, autonomous and hybrid candidate systems tests.

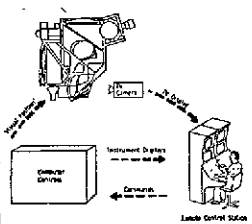
1. Manual System Tests - The test rationale for performing the recommended series of tests for the manual system is summarized in Figure IV-3. The desire was to make use of one facility for a total test series, if possible, to reduce test setup costs and provide an orderly progression of tests. Another consideration is the fact that an end-to-end systems test covering all phases has been proven to be cost effective in the long run. This approach has historically uncovered problem areas which were not anticipated, and allowed testing of transition from phase-to-phase. This approach produces a higher confidence in the results.

The facilities considered for each paase of the test program and the advantages/disadvantages for each are illustrated in Figure IV-4. Each facility selection was made to maximize the use of existing MSFC facilities and minimize the modification to these facilities. The fidelity requirements dictated accurate dynamics and good representation of mission effects (celestial scenes and day/night simulations). Refer to test procedure RIM of Volume III of this report for details.

These requirements are best met by the T27 Space Flight Simulator (SFS) of the MSFC Rendezvous and Docking Laboratory.

FACILITY SELECTION - MANUAL RENDEZVOUS

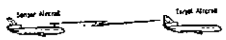
T27 Space Flight Simulator (MSFC R&D Laboratory)



Advantages
- Easily Produces Composite Image
- Minimum Facilities Mods
- Visual Simulations Available (Celestial/Lighting)
- Low Cost

Disadvantages
- Requires Mission Orbit Simulation Increase To Geostationary Altitude
- Scaling Allows 20 Mile Range
- No Full Scale Capability

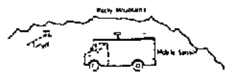
Aircraft Flight Test



Advantages
- Reduced Altitude Effects
- Allows Actual Ranges
- Permits Full Scale Target

Disadvantages
- Requires Two Aircraft
- Not Existing Facility
- High Cost

High Altitude Test (MMC - Denver Area)

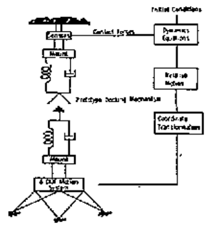


Advantages
- Low Cost
- Full Size Target At Actual Ranges

Disadvantages
- Requires Mobile Power Supply
- Requires Mobile Mini-Computer
- Added Ground-Induced Motion Effects

FACILITY SELECTION - MANUAL DOCKING

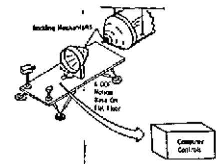
6DOF Motion System



Advantages
- Best Dynamics Simulation
- Flex Body Sim Possible
- Best Tug ACS Simulation
- Full Scale Hardware

Disadvantages
- Limited Travel
- Limited Offsets Available

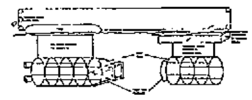
Test Lab Flat Floor



Advantages
- Full Scale Hardware
- Wide Range Of Offsets Available (Initial Conditions)

Disadvantages
- Mass/C.G. Simulation Difficult
- Frictional Effects Limit Fidelity
- Tug Control System Simulation Difficult
- No Flex Body Simulation Capability

Neutral Buoyancy

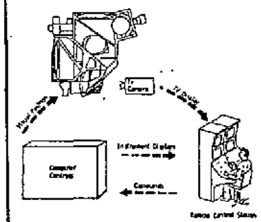


Advantages
- Full Scale Hardware
- Wide Range Of Offsets Available (Initial Conditions)
- Mass/C.G. Simulation Possible

Disadvantages
- Water Viscosity Limits Dynamic Fidelity
- Tug Control System Simulation Difficult
- No Flex Body Simulation Capability

FACILITY SELECTION - MANUAL INSPECTION & CLOSURE

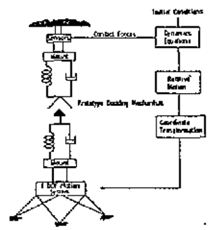
T27 Space Flight Simulator (MSFC R&D Laboratory)



Advantages
- Easily Produces Composite Image
- Minimum Facilities Mods
- Visual Simulations Available (Celestial/Lighting)

Disadvantages
- Requires Mission Orbit Simulations Increased To Geostationary Altitude

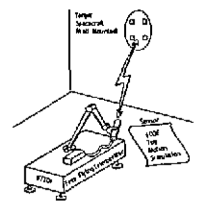
6DOF Motion System (MSFC R&D Laboratory)



Advantages
- Full Scale Target
- 6DOF Motion
- Good Dynamics Fidelity

Disadvantages
- Limited Range Simulation (~35 Ft)
- No Celestial Or Mission Effects Capability

FFTO Flat Floor



Advantages
- Full Scale Target
- Use Of Prototype FFTO Hardware
- Good Tug Dynamics

Disadvantages
- Existing 3DOF Capability Only
- No Target Motion Capability Exists
- No Celestial Or Mission Effects
- Limited Range Capability (~35 Ft)

Figure IV-4. Facility Selection Summary for Manual System Tests

Since scaling is acceptable for the TV sensor, the T27 SFS can be used for ranges out to 20 n mi, tug to target spacecraft separation. This allows the use of the same system for rendezvous, inspection and closure phase tests. However, the performance of the RF rendezvous radar sensor selected for the manual candidate is dependent on the target radar cross-section. The facility selected for testing the primary rendezvous sensor is the high altitude test approach. This method was selected over an aircraft flight test due to costs. It reduces atmospheric effects by operating in the Rocky Mountain area near Denver, Colorado. Details of the test setup and procedures may be found in Volume III of this report.

For the docking tests, the dynamics fidelity requirement is the driver. For this reason the 6 DOF motion system of the MSFC Rendezvous and Docking Laboratory was selected as providing the most realistic dynamics simulations.

2. Autonomous System Tests - The test rationale for performing the recommended series of tests for the autonomous system is summarized in Figure IV-5. The desire was to make use of a single facility as much as possible to reduce test setup costs and provide an orderly progression of tests.

The facilities considered for each phase of the test program and the advantages/disadvantages for each are illustrated in Figure IV-6. Each facility selection was made to maximize the use of existing MSFC facilities and minimize the modification to these facilities. The fidelity requirements dictated full scale target mockups due to sizing and placement of spacecraft mounted aids (e.g., retroreflectors). Further, good dynamics representation is required from the inspection range to final docking.

Since scaling cannot be easily accommodated, the rendezvous phase tests require approximately 25 miles separation between sensor and target. A Shuttle flight test and an aircraft flight were considered to reduce atmospheric effects. An alternative approach which reduces atmospheric effects significantly, but not as much as the other options, is recommended due to cost. This approach involves mounting a target in the Rocky Mountains west of Denver, Colorado and providing a vehicle mounted sensor. The details of this test may be found in Test Procedure R1A, Volume III of this report.

R1A - Acquisition, Tracking & Ranging At Max. Range

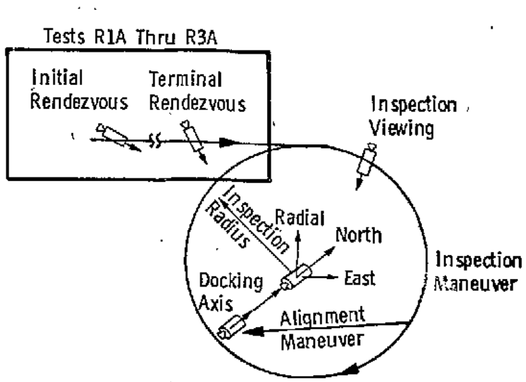
- New Technology Sensors/Software
- Defines Range Specifications
- Uncertainty Of Target Distinguishment From Background
- Lighting Effects

R2 - Rendezvous Algorithm Verification

- New Software Application
- Required To Support Other Rendezvous Tests

R3A - Rendezvous Sensor Tracking

- New Technology Sensors/Software
- Extension Of Test R1A
- Defines Closure Rate Specification



I1A - Automatic Target Tracking

- Reduced Range Requires More Stringent Control
- Determines Lighting/Pointing Constraints
- Defines Range Specification For Sensor

I2A - Automated Target Inspection

- Adds Complexity Of Tracking While Maneuvering
- Refines Inspection Range Specification
- Defines Maneuver Rate/ACS Propellant Usage

I3A - Docking Port Identification

- Determines Additional Orbits Required
- Ascertains Need For Reflectors To Aid In Docking Port Location

I4A - Target Attitude Determination

- Defines Accuracy Of TA Determination Capability
- Refines Target Mounted Aid Specification

I5 - Inspection & Commit-To-Dock Algorithm

- New Software/Decision Algorithm
- Required To Support Other Inspection Phase Tests

C1 - Closure Algorithm Verification –

- New Software/Control Algorithms
- Required To Support Other Closure Phase Tests

C2A - Closure Tracking –

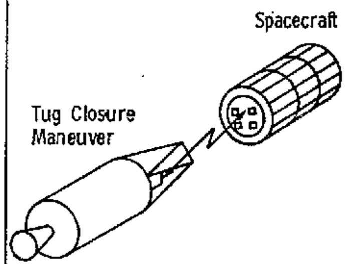
- Reduced Range Requires More Stringent Control
- Establish Closure Rate Specification
- Refines Minimum Range Requirements For Loss Of Sensed Data

C3A - Autonomous Stationkeeping –

- New Application Of Control Software
- Added Complexity - More Stringent Control
- Desirable For Abort Capability
- Establishes Stationkeeping Range Specifications

C4A - Closure Abort –

- New Technology Application
- New Decision Algorithms



Autonomously Monitor/Control

– Range
– LOS Angle
– Target Attitude
– Rates Of Above

D1 - Latch Design & Operations Verification

- New Hardware Design
- Establish Dynamics, Loads And Shock Attenuation Specifications
- Verify Range Of Lateral & Angular Misalignment Accommodations

D2 - Dynamic Effects - Pre- And Post-Latch

- Establish Tug ACS Control Mode Specifications
- Establish Spacecraft Interface Loads, Shock And Vibration Criteria Specifications.

D3 - Docking Abort

- New Technology Application
- New Decision Algorithms

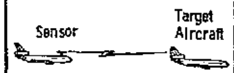
FOLDOUT FRAME 1

Figure IV-5. Test Rationale Summary for Autonomous System Tests

FOLDOUT FRAME 2

FACILITY SELECTION - AUTONOMOUS RENDEZVOUS

Aircraft Flight Test



Advantages
- Reduced Atmospheric Effects
- No Shuttle Schedule Impacts
- Full-Size Target At Actual Ranges

Disadvantages
- Requires Two Aircraft
- Reduced Atmospheric Fidelity

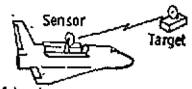
High Altitude Test

(MMC - Denver Area)

Advantages
- Lowest Cost
- No Shuttle Schedule Impacts
- Full-Size Target At Actual Ranges

Disadvantages
- Reduced Atmospheric Fidelity
- Added Ground-Induced Motion Effects

Shuttle Flight Test

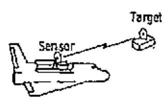


Advantages
- Actual Environment
- Potential Combination With TOBE
- Full-Size Target At Actual Ranges

Disadvantages
- High Cost
- Impacts Shuttle Schedule
- More Applicable To Final System Verification

FACILITY SELECTION - AUTONOMOUS INSPECTION & CLOSURE

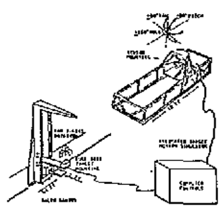
Shuttle Flight Test



Advantages
- Actual Environment (6DOF)
- Potential Combo W/TOBE
- Full-Size Target At Actual Ranges

Disadvantages
- High Cost
- Shuttle Schedule Impacts
- More Appropriate For Final Systems Verification

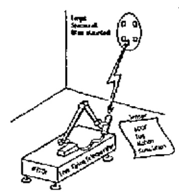
Dalto Gantry & TMS



Advantages
- High Dynamics Fidelity
- Full Scale Target At Approx. Actual Ranges
- No Shuttle Schedule Impacts
- Expandable To 6 DOF

Disadvantages
- Requires Relocation Of TMS
- Existing 4 DOF Capability
- Range Limited To ~50 Ft.

FFTO Flat Floor

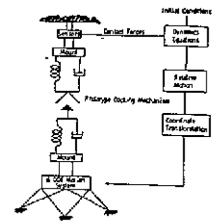


Advantages
- Use Of Prototype FFTO Hdwe
- No Shuttle Schedule Impacts
- Expandable To 6 DOF
- Full Scale Target

Disadvantages
- Existing 3 DOF Capability Only
- No Target Motion Capability Exists
- Range Limited To ~35 Ft.
- Reduces Dynamics Fidelity

FACILITY SELECTION - AUTONOMOUS DOCKING

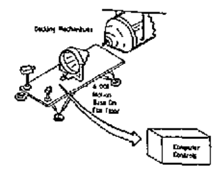
6 DOF Motion System



Advantages
- Best Dynamics Simulation
- Flex Body Sim Possible
- Best Tug ACS Simulation
- Full Scale Hardware

Disadvantages
- Limited Travel
- Limited Offsets Available

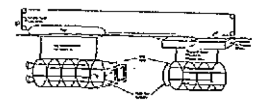
Test Lab Flat Floor



Advantages
- Full Scale Hardware
- Wide Range Of Offsets Available (Initial Conditions)

Disadvantages
- Mass/C.G. Simulation Difficult
- Frictional Effects Limit Fidelity
- Tug Control System Simulation Difficult
- No Flex Body Simulation Capability

Neutral Buoyancy



Advantages
- Full Scale Hardware
- Wide Range Of Offsets Available (Initial Conditions)
- Mass/C.G. Simulation Possible

Disadvantages
- Water Viscosity Limits Dynamic Fidelity
- Tug Control System Simulation Difficult
- No Flex Body Simulation Capability

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Figure IV-6. Facility Selection Summary for Autonomous System Tests

The inspection and closure phase test requirements fit the combined capability of the Dalto Gantry and Target Motion Simulator (TMS) as modified. The Test setup is described in Test Procedure RI1A, Volume III of this report and requires relocation of the TMS within the MSFC rendezvous and docking laboratory.

The docking phase test requirements are the same for autonomous and manual systems and, therefore, the same facility is recommended. Refer to Test Procedure D1 in Volume III of this report for details of the test setup.

3. Hybrid System Tests - The hybrid system selection was accomplished differently than the manual and autonomous candidates. Nineteen (19) manual candidates and twenty-four (24) autonomous candidates met the basic requirements set and were ranked using "desirability" criteria. From the highest ranked manual and autonomous systmes a hybrid "best mix" candidate was derived to overcome weaknesses in the other areas. Following this approach, the subsystem identified for a given sensor, strategy or mechanism accompanies that selected element for the hybrid system.

However, the recommended approach to the hybrid system development presumes a parallel activity for a manual and an autonomous capability from which the hybrid system evolves. The selected candidate hybrid system tests are, therefore, a delta or tests in addition to the manual and autonomous test program.

These additional tests are basically in three categories for which interactions are introduced. The rationale for these tests are summarized in Table IV-2.

Table IV-2. Hybrid Tests Verify Interactive Elements

Interface Verification
- Assure Selected Manual Subsystems & Autonomous Subsystems Work Together
- Assure Inputs From Primary And Backup Sensor Subsystems Are Not In Conflict For All Test Phases

Control Handover Procedures
- Validate Procedures For Phase Related Transfer Of Primary Control From Autonomous To Manual Or Vice-Versa
- Validate Capability To Implement Overrides Or Backup From Remote Console

Software Hierarchy
- Insure Mode Changes Are Programmed In Tug Control System Software To Respond To Correct Inputs, If Conflicting Instructions Are Received
- Perform Entire Simulated Mission Sequences Using Total Software For Validation

No interactions are foreseen in the rendezvous phase since the automated sensor is in control and the manual sensor (TV) is used only to backup the rendezvous. In the docking area, both the manual and autonomous systems use the same test program. This is possible since the docking test objectives are primarily mechanism oriented and are not changed by the method of bringing the Tug and spacecraft mechanisms together.

The major area of hybrid system test activity is in the inspection and closure phase tests. The impacts on simulation/demonstration facility elements for the hybrid candidate are in the interface verification, control handover and software heirarchy areas previously discussed. This can be accommodated by control software in the MSFC rendezvous and docking laboratory hybrid computers as indicated by Figure IV-7.

Test Phase	Autonomous	Hybrid	Manual
Rendezvous Phase Test	High Altitude Test	Independent Sensor Usage (No Impact)	High Altitude Test & T27 Space Flight Simulator
Inspection & Closure Phase	Dalto Gantry & Target Motion Simulator	Combination Test Interface Via Control Software	T27 Space Flight Simulator
Docking Phase Test	6DOF Motion System	Same (No Impact)	6DOF Motion System

Figure IV-7. Hybrid System Test Facility Implications

D. TEST PLANS/SCHEDULES/COST

The test planning and scheduling activity utilized the priority risk assessment and scheduling predecessor requirements previously discussed. The overview test plan is illustrated in Figure IV-8.

The autonomous candidate development status is such that sensor SRT should be started early to allow longer lead time based on a technical risk assessment. This overview illustrates a time-phased plan which develops a rendezvous and docking system for use in retrieval of spacecraft by the Space Tug. This approach permits developing an autonomous and a manual system, learning the merits and limitations of each, and selection a "best mix" hybrid system. However, it should be noted that the schedule is adaptable to developing a system

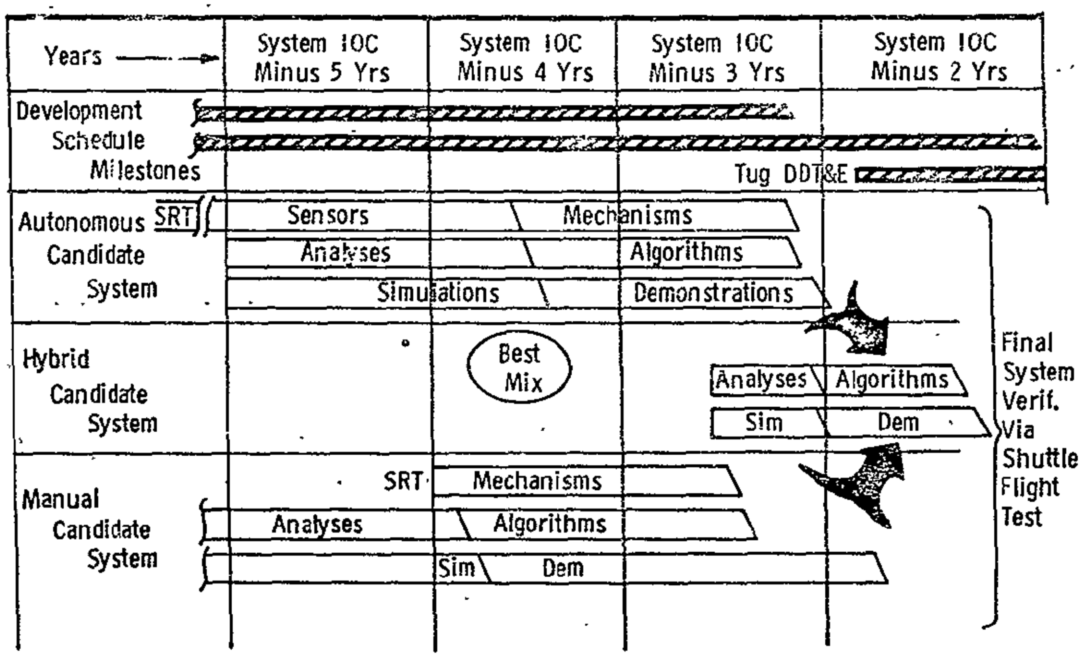

Figure IV-8. Test Plan Overview

which could be used with other vehicles, if desired. For example, the system de-development could be keyed to a manned Tug program, space station elements, or gang on-orbit scenario for other applications. This could be accommodated by defining a new set of requirements and subjecting the selected systems to a similar test plan.

The scheduling tools previously discussed were used in developing a schedule for each candidate. Priority risks for each test were developed with the test requiring the most development ranked first. Specifically, the autonomous abort has highest technical risk and should be scheduled first from this aspect. However, other factors must be considered, such as scheduling constraints and predecessor requirements. As an example, for the autonomous abort there must be some analyses which precede the abort test; hence, these analyses become predecessor requirements for the autonomous abort simulation/demonstration. Also, a normal closure procedure should be demonstrated and well understood before the abort capability is verified.

Both priority risk and scheduling predecessor requirements are summarized in Table IV-3.

Table IV-3: Predecessor Requirements trade with risks for schedule development

Test Ident. (Risk Priority)	Test Title	Scheduling Predecessor Requirements			
		Test	SRT	Analysis	Software
R1A (12)	Autonomous Acq. Track And Rng. @ Max. Range		Sensor(s) SRT		
R1M (3)	Manual Acq. Track And Rng. @ Max. Range		SC Mounted Aids (Hdwe SRT)	Range/Rate Methods	Range/Rate Algorithms
R2 (19)	Rendezvous Algorithms Verification			Strategy Implementation Analysis	
R3A&M (15)	Rendezvous Sensor Track	R1A Or R1M.	Sensor(s) SRT	Tracking Methods	Rendezvous Algorithms
I1A (14)	Autonomous Tgt. Track	(15) Extension of R1A	Sensor(s) SRT	Strategy Implem. Anal.	Recognition/Ranging
I1M (6)	Manual Tgt. Track	(15) Extension of R1M	Image Interpretation Hdwe/SW SRT	Strategy Implem. Anal.	Lock-On Algor.
I2A (7)	Auto Target Inspection	(15) Possible Combine W/I3A & I4A	Sensor(s) SRT		Recognition/Ranging Lock-On Algor.
I2M (22)	Manual Target Inspection	(15) Poss. Combine W/I3M & I4M		Tug Dyn. Fidelity	Recognition Algorithms Data Compress
I3A (8)	Autonomous Dock Port Identification	(15) Poss. Combine W/I2A & I4A	Sensor(s) SRT SC Mounted Equip.	Cue Definition	Target Recognition Algor.
I3M (5)	Manual Dock Port ID	(C3MTSU) (15) Poss. Comb. W/I2M & I4M	SC Mounted Equip.	Cue Definition	Target Recognition Algor.
I4A (16)	Autonomous Target Attitude Determination	(15) Possible Comb. W/I2A & I3A	Sensor(s) SRT SC Mounted Equip.	Cue Definition	Attitude Computation Algor.
I4M (4)	Manual Target Attitude Determination	(15) Possible Comb. W/I2M & I3M	SC Mounted Equip.	Cue Definition	Attitude Computation Algor.
I5 (9)	Inspection & Commit-To-Dock Algorithms Verif.				(R/R/LOS/TA) Conversion Meas. Data To Control
C1 (20)	Closure Algorithms Verif.			Strategy Impl. Analysis	Tug Control Via Sensed Data
C2A (18)	Auto Track During Closure	(C1) Common W/I4A & C3A	Sensor(s) SRT	Data Compress	Tug Control Via Sensed Data
C2M (17)	Manual Track During Closure	(C1) Common W/I1M & I4M			
C3M (11)	Manual Stationkeeping	C2M		Man Response - Data Compress	Tug Fine Mode Control Laws - Attitude & Position Hold SW
C3A (2)	Autonomous Stationkeeping	C2A	Prox. LED Sensor Dev (Hdw/SW)	Stationkeep Strategy Anal.	Stationkeep Algorithm
C4A (1)	Abort Procedures - Autonomous	Normal Proc. Verification	Hdwe SRT/Sensor SRT	FMEA (Detect/Correct)	Failure Detection/ Correction SW
C4M (13)	Abort Procedures - Manual	Normal Proc. Verification	Hdwe SRT	FMEA (Tug & SC)	Failure Detection Algor.
D1 (10)	Mechanism Design & Operations		Mechanism Hardware SRT		
D2 (21)	Dynamic Effects - Pre-& Post Latch			Dyn. Anal. - Control Mode	Dyn. Sim. - Tug Control Gain Changes
D3 (23)	Docking Abort	Normal Dock Verification		FMEA/Undock	

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Confidence levels are the inverse of technical risk priority and relate to the development lead time required for each test phase. Table IV-4 illustrates the confidence level definitions and categorizes the test into these levels by mission phase.

Table IV-4. Test Phases Relate to Confidence Levels

Definition Of Confidence Level Groups

	Level 1 Low	Level 2 Medium-Low	Level 3 Medium-High	Level 4 High
R&D PT&E	Substantially Beyond The State Of The Art. Three Years Or More Of R&D PT&E Required.	Slightly Beyond The State Of The Art. Two To Three Years Of R&D PT&E Required.	Within The State Of The Art. No Qualified Hardware Exists. One To Two Years Of R&D PT&E Required.	Modification Of Existing Hardware. Less Than One Year R&D PT&E Required.
Cost	Total Lack Of Data. Inadequate Time Provided To Make Estimate. Estimate Is Almost A Poor Guess.	Detailed Design And Cost Data Not Sufficient To Make Accurate Estimate. Time Allowed Makes Estimate Uncertain.	Detailed Design And Cost Data Were Available. Could Be More Accurate If More Time Were Available. Could Have A Few Minor Errors.	Sufficient Time And Data Available To Provide Accurate Estimate.
Schedule	Inadequate Time And Data Available To Make Estimate. Schedules Are Extremely Tight With Almost No Possibility Of Meeting All Dates.	Time Allowed Makes Estimate Uncertain. Input Data Are Inconsistent And Questionable. Schedules Are Tight - No Allowance For Delay.	Sufficient Time And Data Available To Estimate In Depth. Schedules Allow Time For Minor Delays.	Sufficient Time And Data Available To Estimate In Depth. Schedules Allow For Major Delays.
Performance Level	Performance Just Above The Minimum Acceptable.	Many Performance Objectives Are Met.	Most Performance Objectives Are Met.	All Performance Objectives are Met Or Exceeded.

Candidate Test Groupings

Conf. Level / System	Level 1 Low	Level 2 Med-Low	Level 3 Med-High	Level 4 High
Autonomous	Closure Tests (C1 Thru C4A)	Inspection Tests (I1A Thru I5)	Rendezvous Tests (R1A Thru R3A)	Docking Mechanism Tests (D1 Thru D3)
Manual	None	Rendezvous & Inspection Tests (R1M Thru R3M And I1M Thru I5)	Closure Tests (C1 Thru C4M)	Docking Mechanism Tests (D1 Thru D3)

Schedules are presented in Figures IV-9, -10 and -11 for development of the autonomous, manual and hybrid candidates, respectively. These schedules are at an individual simulation/demonstration test level and identify the associated analyses, software development and SRT activities which support the tests. Additional detail for the SRT and analyses tasks may be found in the SRT plan of Volume III and the recommendations section of this volume of the report.

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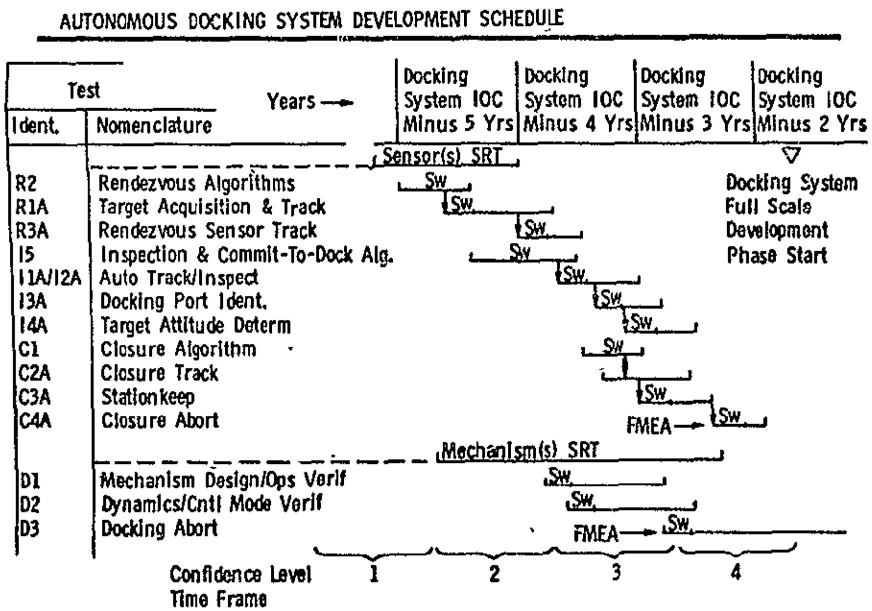


Figure IV-9: Autonomous Test Schedule

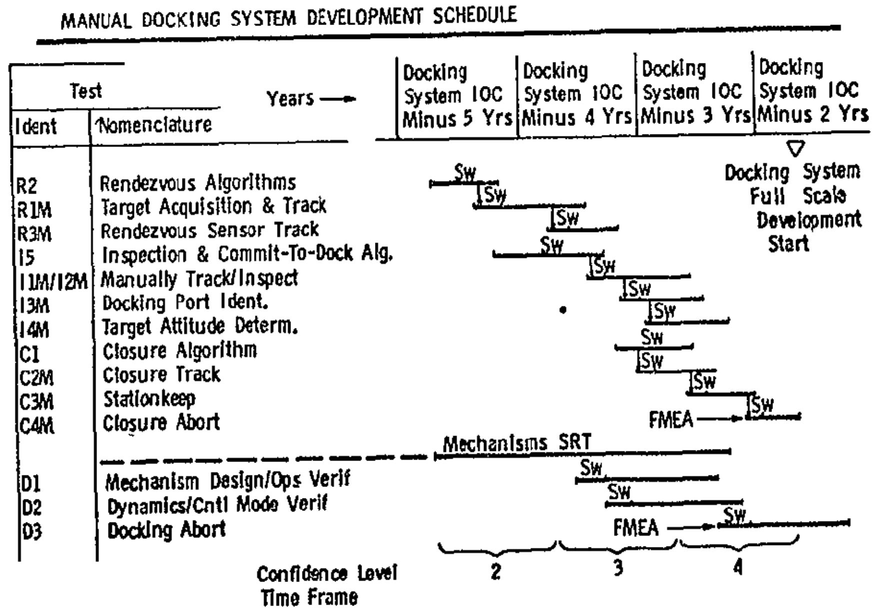
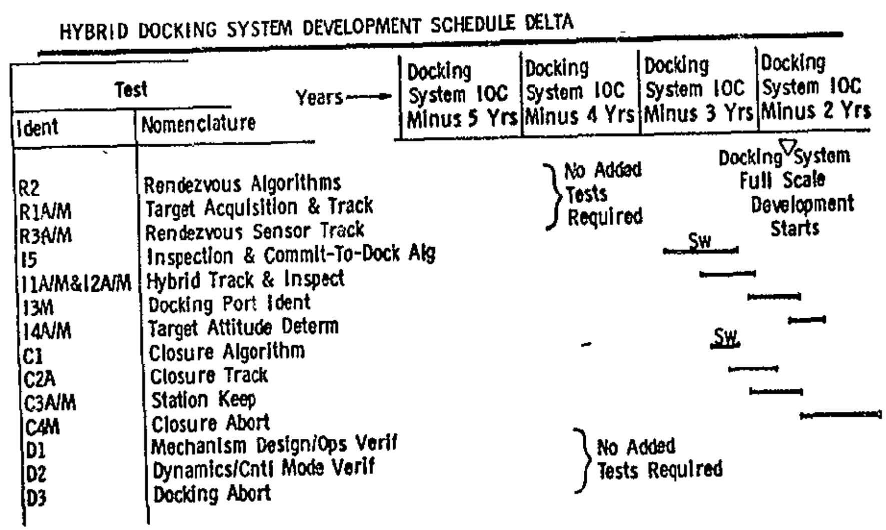


Figure IV-10: Manual Test Schedule



Note: Subscript A And/Or M Following The Test Identifier Indicates The Test Selected Which Represents The "Best Mix" Philosophy Which Accompanies The Selected Subsystems.

Figure IV-11: Hybrid Delta Test Schedule

V. RECOMMENDATIONS

This study has identified three general categories of future activity that should be conducted in support of planned and potential STS rendezvous and docking objectives. These include Supporting Research and Technology, a Rendezvous and Docking Integration activity, and the Simulation/Demonstration activity. The SRT activity includes long lead effort and activity that will keep design options open until a sound technical basis fo deletion can be developed. The R/V&D integration activity is required to assemble myriad future applications requirements into a cohesive approach to system development and operation that will maximize program cost effectiveness. The simulation/demonstration activity provides a medium for making rational system selections and proving concepts before entering into full scale development. Careful planning and faithful implementation of these activities assures the most effective use of program funding

A. SUPPORTING RESEARCH AND TECHNOLOGY (SRT)

The technology for autonomous rendezvous and docking capability represents new hardware and software developments. The hardware SRT can be categorized into sensor and mechanism developments. The software covers broad categories of maneuver strategy, sensor utilization algorithms and decision algorithms. An SRT plan is presented in Volume III, Part II of this report and is subdivided into Sensor SRT Tasks (S-1 through S-4), Algorithm SRT Tasks (A-1 through A-7) and Mechanism SRT Tasks (M-1 through M-3). A summary of the areas where SRT activities are concentrated is presented in Table V-1.

B. RENDEZVOUS AND DOCKING INTEGRATION

One concern that arose during the course of this study was that the resulting designs were tailored to specific roles, particularly retrieval of a given catalog of anticipated spacecraft with all-up Tug. Recent statements regarding future space programs indicate the family of space systems may be expanding to include such elements as the manned OTV, space stations deployed at low and geostationary altitudes, and possibly more visionary programs. Emphasis shift from retrieval to servicing of automated spacecraft appears probable. It is proposed that a broad scope systems study be done to evaluate all possible uses and users

SRT Candidates -

Hardware SRT -

- Autonomous Sensor Development (SLR, RF Radar)
- Target Mounted Aids (Retro Reflectors, Patterns, Etc.)
- Non-Impact Docking Hardware (STEM, Sensors, Etc.)
- Failure Detection Sensors

Software SRT -

- Image Data Compression
- TV Pattern Recognition Algorithms (Smart Bomb, Etc.)
- Failure Recognition/Abort Algorithms

Analyses/Study Recommendations -

- Software Requirements Studies, All Phases
- Tug Control Responses Using Docking Sensor Inputs
- Failure Modes & Effects Analyses (Functional Level)
- Manned Tug Requirements Impact Analyses
- Servicing Roles
- Shuttle Flight Test Definition

Table V-1. SRT Activity Summary

of a rendezvous and docking system. The objective of this study would be to identify potential for commonality among programs and provide for a greater flexibility in design to accommodate the multiple purposes that will evolve from the broader application of the system.

Another rather broad conclusion was reached with regard to the payload integration task that will evolve as new space systems become operational, and the number and variety of users grow in the years ahead. Any payload desiring more than simple deployment will interface with STS through what could, and should, be a common system; the Rendezvous and Docking System. This interface role leads to the conclusion that the R/V&D system should be a part of the total STS payload integration effort, rather than constrained to a specific STS vehicle, such as the Space Tug. It appears that a developmental/operational role for a rendezvous and docking integrator should be implemented.

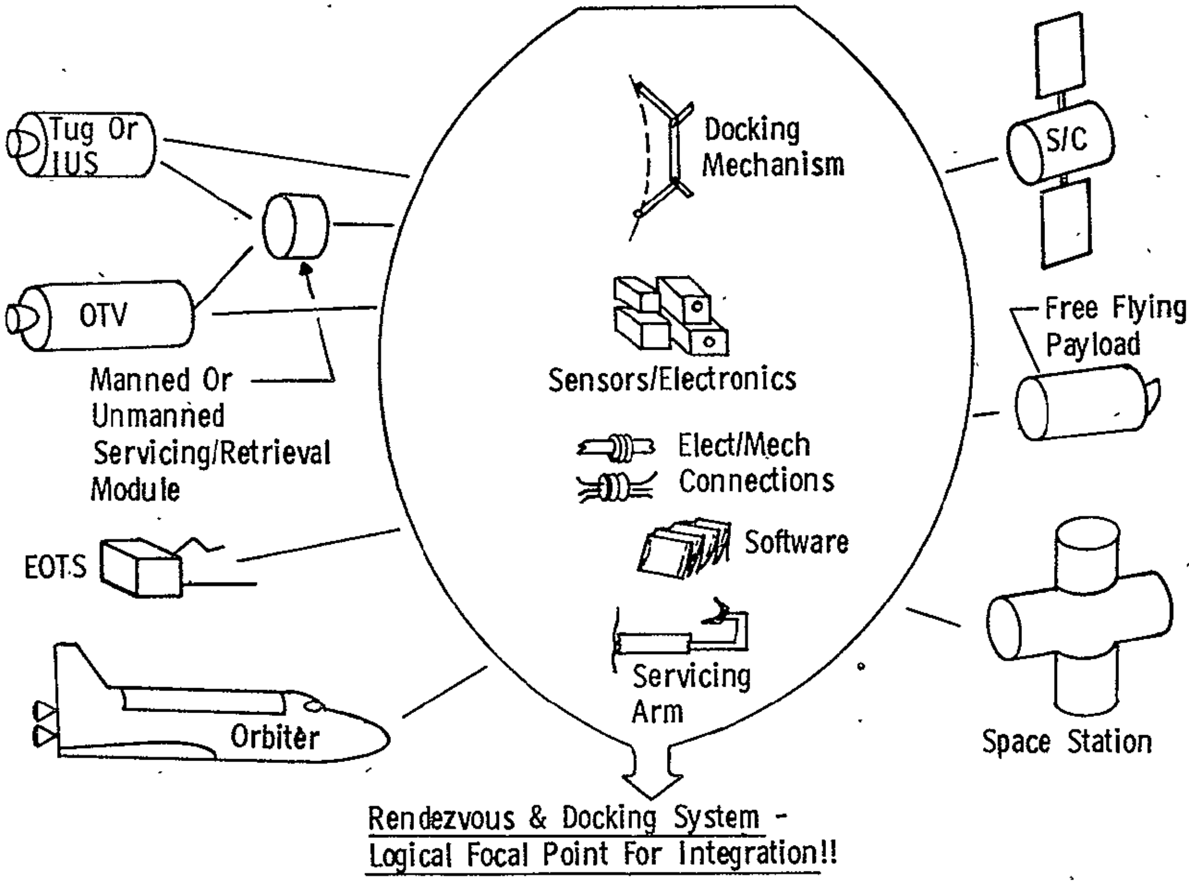


Figure V-1. Retrieveable/Serviceable Payload Integration

The nature of the interfaces that exist between STS elements and the spacecraft community are illustrated in Figure V-1. These interfaces are closely interrelated; payload integration and rendezvous and docking tasks are closely allied. Many of the tasks involved in payload integration are required to arrive at a rendezvous and docking system. Creation of a broad integration role encompassing both rendezvous and docking, and payload integration seems desirable for the following reasons:

- The major interface between STS elements and spacecraft is through the rendezvous and docking system.
- STS and payload designers are preoccupied with internal design problems.

- An integrator can act as an unbiased negotiator between STS and the spacecraft community.
- The integrators broad knowledge will provide an efficient transition to the operational phase.

Should this integration role be sanctioned, the tasks required to define and implement the required development and operational activities are as follows:

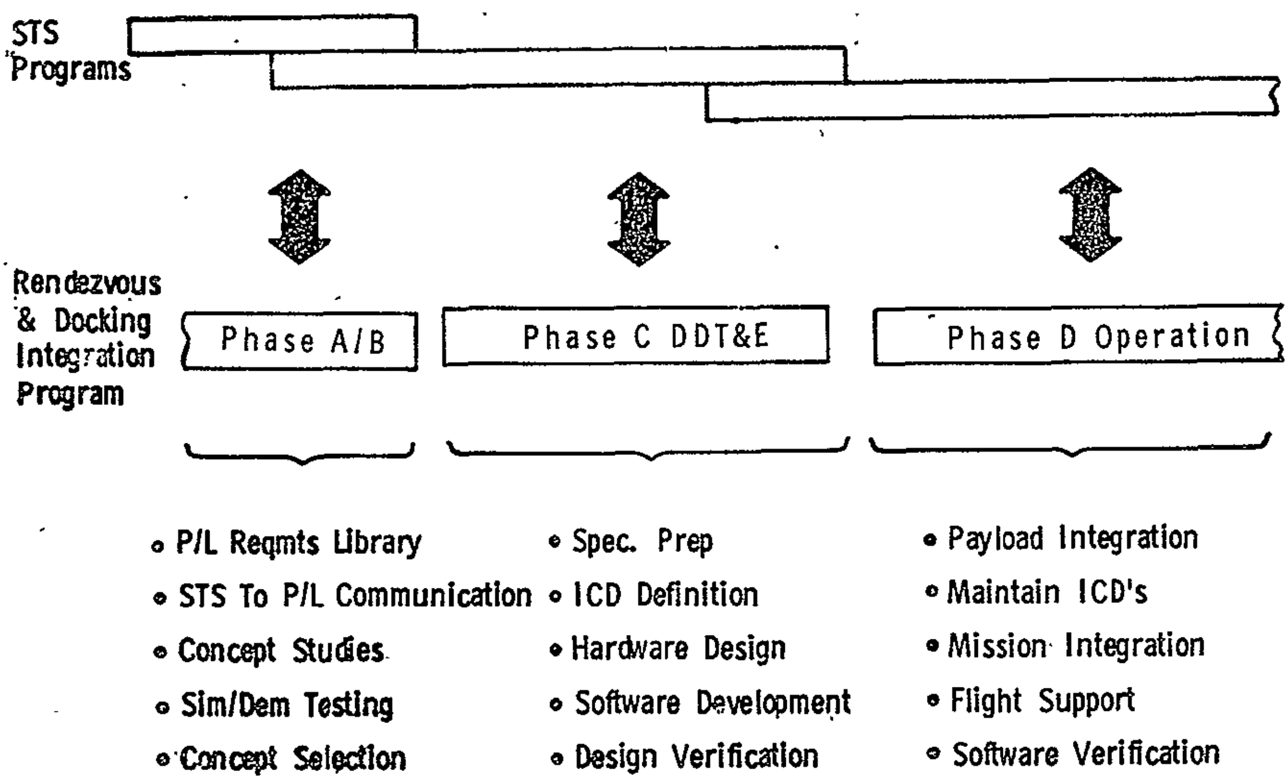


Figure V-2. Integration Task Content

The integration tasks required fall into the three categories indicated in Figure V-2. Phase A/B tasks are required, starting as soon as possible. An initial definition task should span one year. Its objective would be to define an integrated approach to rendezvous and docking system development and operation that meets all STS objectives. Then the Phase B effort should be broadened to encompass the total payload integration effort, and scoped to permit specific definition of each identifiable application. Phase C DDT&E activity must follow

a common thread developed in the Phase A/B activity, but must be pointed particularly to support specific operationa requirements. Those recognized at this time are Shuttle rendezvous activity, IUS servicing missions, EOTS missions, and OTV missions (beginning with geostationary space station assembly). Phase D activity is oriented at operational support, an area where payload integration and rendezvous and docking mission planning are key continuing roles. The approximate schedule of these integration activities is shown in Figure V-3.

Table V-2 outlines the first step in the implementation of the Rendezvous and docking System Integration role. As noted, the objective is to bring the many R/V&D requirements anticipated in the STS era into a common perspective. It is necessary to understand all objectives, and to evolve a comprehensive approach that will yield the most cost effective path to achieving all these objectives. The study outlined will provide that common base that leads to efficient utilization of available funding. The most important specific output of this study will be system interface definitions that will assure future STS vehicles, spacecraft, and ground support facilities will be able to effectively meet anticipated operational goals involving rendezvous and docking.

C. SIMULATION/DEMONSTRATION RECOMMENDATIONS

A simulation/demonstration activity is considered to be a key element in the development of remote rendezvous and docking capability for the STS era. The development program defined during this study includes SRT activities and analyses which should precede simulation/demonstration tests. The tests are separated into manual and autonomous systems procedural sets. It is recommended that these efforts be pursued concurrently and the hybrid system tests only be deltas to address interactions and interfaces which result from bringing manual and autonomous elements together in a hybrid "best mix" system.

A simulation/demonstration test program was specified which maximized usage of existing MSFC facilities. The test program provides an end-to-end systems test flow demonstrating all phases of a rendezvous and docking mission. Test Descriptions and Test Procedures were developed and are presented in Parts III and IV, respectively, of Volume III of this report. A Facilities Modification

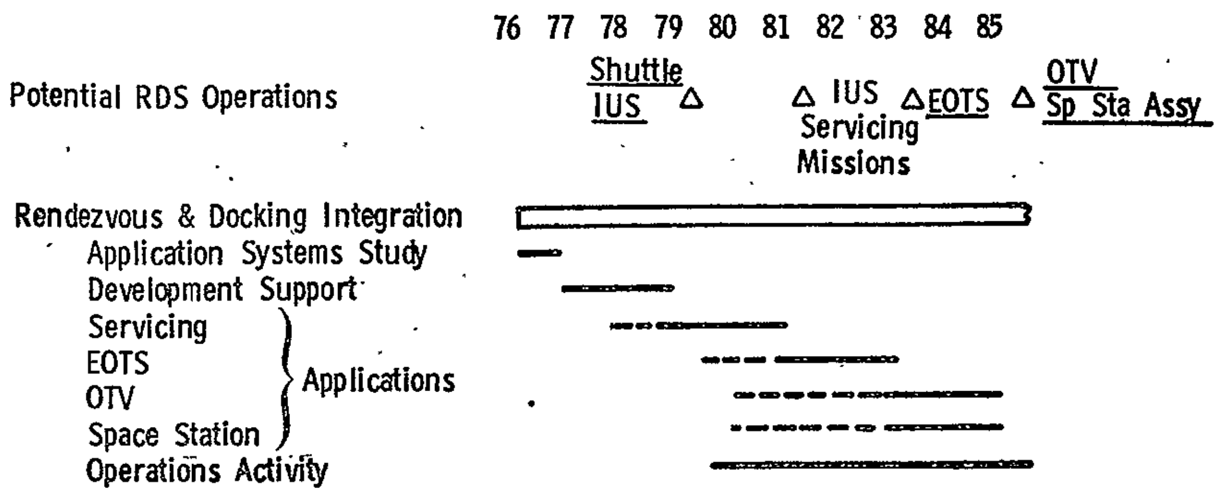


Figure V-3. Integration Task Schedule

Table V-2. Rendezvous and Docking Applications Systems Study

Objective:

Define An Integrated Approach To Rendezvous And Docking System Development And Operations That Meets All STS Objectives

Approach:

- System Requirements Generation
  - Compile Planned & Projected STS Rendezvous & Docking Activity
  - Conduct Functional Operations Analyses
  - Develop Time Phased System Requirements
- Integrated Development Approach
  - Develop Technique/Mechanization Alternatives
  - Define Time Phased Development Paths
  - Select & Define The Most Effective Development Approach
- Integrated Operational Approach
  - Develop Alternative Operational Concepts
  - Select & Define The Most Effective Operational Approach
- System Interface Definitions
  - RDS/STS Vehicles
  - RDS/Retrievable-Servicable Spacecraft
  - RDS/Flight Support Systems

Plan (Part V of Volume III) details the necessary minor changes to existing MSFC facilities to meet the test requirements.

The overall development program recommendations are summarized in Table V-3.

Table V-3. Rendezvous & Docking System Development Recommendations

• Simulation/Demonstration Tests -	Make Maximum Use Of Existing MSFC Facilities, With Growth Options
• Shuttle Flight Test -	Provides Ideal Test Bed For Final Systems Verification - Possible Combine Wtih Teleoperator Bay Experiment (TOBE)
• SRT & Analyses -	Autonomous Sensor SRT And Some Mechanism Long Lead Work Is Foreseen. Software Analysis And Requirements Definition Should Be Started Early To Allow Checkout And Assure Software Readiness To Support The Testing
• Options Available -	Autonomous/Manual Rendezvous And Docking Systems Applicability To Manned Tug To Space Station Resupply/Rescue And Payload/Payload Gang On-Orbit (Commonality With Shuttle Orbiter To Payload Rendezvous/Docking)

The key issues which surfaced in the simulation/demonstration area as a result of the present study, as well as those issues which should be considered in future efforts, are summarized above.

The current set of requirements are somewhat limited in scope. A rendezvous and docking system should be developed and demonstrated independent of space tug development. The need for a system of this kind is foreseen associated with Earth Orbital Teleoperator System (EOTS) placement/retrieval of large automated satellites which are susceptible to contamination, and other payload-to-payload docking applications such as space station build-up/assembly on-orbit. The potential use of an expendable IUS for servicing of spacecraft should not be dismissed lightly. This capability would be especially attractive for an expensive spacecraft exhibiting infant mortality.